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Recovery potential assessment of Roundnose Grenadier (*Coryphaenoides rupestris* Gunnerus, 1765) in Northwest Atlantic waters

Évaluation du potentiel de rétablissement du Grenadier de roche (*Coryphaenoides rupestris* Gunnerus, 1765) dans les eaux de l'Atlantique Nord-Ouest

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ABSTRACT

In 2008, Roundnose Grenadier (*Coryphaenoides rupestris*) was designated as endangered in the Northwest Atlantic by the Committee on the Status of Endangered Wildlife in Canada; based on declines noted in research trawl surveys conducted by Fisheries and Oceans Canada over 1977-2007 in NAFO Div. 2J3K. There has been no directed fishery for Roundnose Grenadier in Canadian waters since 1997, but it does occur as bycatch in other directed fisheries inside and outside Canada's 200-mile limit; especially in the Greenland Halibut fishery. A Bayesian state space implementation of the Schaefer surplus production model was used to estimate population parameters of Roundnose Grenadier in Canadian waters. Catch, bycatch, stock biomass estimates from Canadian research vessel autumn surveys, and commercial catch per unit effort data from NAFO and Canadian Fisheries Observers were incorporated into the model. Projections were made 20 years forward using various levels of fishing mortality; in order to estimate the impact on recovery potential of this species. These models predicted that catch levels above 1.25 $kt \cdot year^{-1}$ likely result in population decline. At a bycatch level of 1 $kt \cdot year^{-1}$, slow recovery of Roundnose Grenadier is predicted. Continued monitoring of abundance and biomass, and any reductions in commercial bycatch of Roundnose Grenadier in other directed fisheries, may prove crucial to the slow recovery of this population over many years. Given the sources of uncertainty described herein, this paper provides an assessment of the recovery potential of Roundnose Grenadier in the Northwest Atlantic, and updates catch data on this species from research vessel surveys and commercial fisheries prosecuted in Canadian waters and in the NAFO Regulatory Area. In the absence of data suggesting local adaptation and genetic differentiation for this species in the Northwest Atlantic, this paper also considers that Roundnose Grenadiers comprise a single Designatable Unit in these waters.

RÉSUMÉ

En 2008, le Grenadier de roche (*Coryphaenoides rupestris*) a été désigné comme étant une espèce menacée dans l'Atlantique Nord-Ouest par le Comité sur la situation des espèces en péril au Canada, d'après la diminution notée dans les relevés de recherche au chalut menés par Pêches et Océans Canada au cours de la période 1977-2007 dans les divisions 2J3K de l'OPANO. Il y n'a pas eu de pêche dirigée du Grenadier de roche dans les eaux canadiennes depuis 1997, mais cette espèce est pêchée sous forme de captures accessoires dans le cadre d'autres pêches dirigées à l'intérieur et à l'extérieur de la limite de 200 milles du Canada, et surtout de la pêche au flétan du Groenland. La mise en œuvre sous forme d'espace d'états bayésiens d'un modèle de production excédentaire de Schaefer a été utilisée pour estimer les paramètres de population du Grenadier de roche dans les eaux canadiennes. Les estimations de captures, de captures accessoires et de biomasse du stock provenant des relevés d'automne des navires de recherche canadiens, ainsi que les données des captures commerciales par unité d'effort provenant de l'OPANO et des observateurs des pêches du Canada ont été incorporées dans ce modèle. Des projections ont été réalisées pour les vingt années à venir à l'aide de divers taux de mortalité par pêche, afin d'estimer l'impact sur le potentiel de rétablissement de cette espèce. Ces modèles ont prédit que des niveaux de capture supérieurs à 1,25 $kt \cdot an^{-1}$ provoqueraient probablement une diminution de la population. À un niveau de captures accessoires de 1 $kt \cdot an^{-1}$, un lent rétablissement du Grenadier de roche est prévu. La surveillance continue de l'abondance et de la biomasse, et toute réduction des captures accessoires commerciales du Grenadier de roche dans le cadre d'autres pêches dirigées, peuvent s'avérer cruciales pour le lent rétablissement de cette population sur de nombreuses années. Compte tenu des sources d'incertitude décrites aux présentes, ce document fournit une évaluation du potentiel de rétablissement du Grenadier de roche dans l'Atlantique Nord-Ouest, et met à jour les données de capture de cette espèce provenant des relevés des navires de recherche et de la pêche commerciale réalisés dans les eaux canadiennes et dans la zone de réglementation de l'OPANO. En l'absence de données suggérant une adaptation locale et une différenciation génétique de cette espèce dans l'Atlantique Nord-Ouest, cet article considère également que les Grenadiers de roche constituent une seule unité désignable dans ces eaux.

INTRODUCTION

Roundnose Grenadier (*Coryphaenoides rupestris* Gunnerus, 1765) is a widely-distributed species of the Family *Macrouridae*: found along the continental slope from North Africa, Europe, Iceland, Greenland, Canada, to the southeastern United States, and along the mid-Atlantic ridge as far south as 20°N in the eastern Atlantic (Cohen et al. 1990). In the Northwest Atlantic, it ranges from Cape Hatteras north to Baffin Island and Greenland (Atkinson 1995*b*). An isolated capture of two specimens was reported in the Bahama Islands (Cohen et al. 1990). In the eastern Atlantic, it occurs from Norway south to North Africa (Kelly et al. 1997). Roundnose Grenadier is a deepwater species found at depths of 180-2600 m; primarily occurring at 400-1200 m (Haedrich and Merrett 1988; Cohen et al. 1990; Savvatimsky 1998).

Roundnose Grenadier has been listed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). This status was determined from the declines noted from research surveys conducted by Fisheries and Oceans Canada (DFO) in NAFO Div. 2J3K. If listed under the Species at Risk Act (SARA) as endangered or threatened, activities that would harm the species would be prohibited and a recovery plan would be required. The three main goals under SARA include: preventing a species from becoming extinct or extirpated, providing a recovery plan, and managing the species to prevent extinction.

BIOLOGY AND LIFE HISTORY

Morphology of Roundnose Grenadier is typical of Macrourids (Fig. 1): medium brown to greyish in colour with black to brownish orbits, mouth, gill cavities, and fins (Cohen et al. 1990). They can reach total lengths (TL) >100 cm (ibid.), but have a relatively short abdominal region; thus much of this length consists of a long, whip-like tail which tapers to a sharp point (Scott and Scott 1988).

Roundnose Grenadier has a broad, rounded snout with a small chin barbel. Its teeth are small, slender, and crowded together; forming a long band that narrows posteriorly (Food and Agriculture Organization of the United Nations - FAO 2009). This species is distinguished from other North Atlantic Grenadiers by its relatively short, compressed head (about 15 % of total body length), and a soft, rounded nose (hence its common name) with a small, button-shaped scute at the tip (Scott and Scott 1988; FAO 2009). Grenadiers also have specialized swim bladders that function at great depths and pressures. Lipids present in the wall of the swim bladder help prevent the loss of air through diffusion: an adaptation to life in deepwater (Wittenberg et al. 1980).

In the Northwest Atlantic, Roundnose Grenadiers have a preferred temperature range of 3.5–4.5 °C, and seem to form dense concentrations where warm water lies directly above the bottom (Scott and Scott 1988; Atkinson 1995*b*). In the Northeast Atlantic, they are found in warmer waters near 6 °C (Atkinson 1995*b*). This species also appears to prefer areas of weak or absent currents: they form dense concentrations in troughs, gorges, terraces, and lower parts of a slope (Zaferman 1992). Zaferman (1992) found this species in aggregations above peaks and slopes of seamounts on the North Atlantic Ridge. Off of the New York and New England states, Roundnose Grenadiers prefer canyon areas rather than an open slope (Snelgrove and Haedrich 1985). Larger fish are usually found further north, and in deeper water (Atkinson 1995*b*).

Roundnose Grenadier were observed shifting their distribution into deeper waters during the late 1980s and early 1990s. Water temperatures in the Northwest Atlantic began to cool in

1975-83; coincident with this change in distribution. Bottom temperatures at depths occupied by this species are relatively constant: changing only by tenths of a degree between years. In the Northeast Atlantic, Roundnose Grenadier occupies warmer waters of 3-11.5 °C (Bridger 1978). Other unknown factors may be affecting their distribution (Atkinson 1995*b*). There is still debate over their migration patterns; requiring more in-depth research.

Roundnose Grenadiers have been found at 100 m depths, but factors that affect their vertical distribution patterns are also not well known. Grenadiers undergo diurnal vertical migrations that can move them more than 1,000 m off the bottom (Cohen et al. 1990); but explanations for such movement conflict with respect to timing and purpose (Atkinson 1995*b*). Roundnose Grenadiers may seasonally move up and down the Continental Slope (Cohen et al. 1990; Atkinson 1995*b*). Based on catch rates off northeastern Newfoundland and Labrador, they appear to move into deeper water in winter, and shallower water towards the end of summer; possibly in pursuit of prey, or in relation to water temperature (Atkinson 1995*b*).

Roundnose Grenadiers undertake vertical migrations from the bottom to feed on a variety of small crustaceans (e.g., shrimp, amphipods, mysids), squid, and small fish such as lantern fish, deepsea smelts, and sculpins (Whitehead et al. 1986; Cohen et al. 1990; Atkinson 1995*b*). As with many deep-water species, young Grenadiers feed mainly on copepods and amphipods; becoming more piscivorous as they grow in length (Magnusson and Magnusson 1995).

It has been suggested that feeding is seasonal, occurring predominantly during autumn (Scott and Scott 1988). Podrazhanskaya (1971) also found that stomach fullness increased during September through December. During this period, Grenadiers may move to the upper continental slope where food is more abundant.

This species is sexually dimorphic: females are larger and heavier than males (Savvatimsky 1985; Kelly et al. 1997). Examination of Brody growth coefficients, K (males = 0.13, females = 0.1), further indicated slow growth rates in these fish (Kelly et al. 1997; Clarke et al. 2003; Baker et al. 2009). It should be noted that measuring total lengths of Roundnose Grenadier at sea can be difficult. Their tails are often damaged or missing when caught by DFO research trawls; therefore, pre-anal fin length (AFL) is measured instead of total length (TL). AFL is measured in a straight line from the tip of the Grenadier's nose to the base of the first anal-fin ray, as adopted by NAFO in June 1980 as standard measurement for Roundnose and roughhead Grenadiers (Atkinson 1991).

Maturation of Roundnose Grenadier seems to be a function of size rather than age (Kelly et al. 1997). Lengths at which 50 % of the population is mature have been reported to be 48 cm for males and 57 cm for females (Bergstad 1990; Clarke et al. 2003). This corresponds to an age of 10 years in females. The age at which all females appear to be mature is 16-17 years (Bergstad 1990; Lorance et al. 2001*a*). Although exact lengths at maturity are debated, it is generally agreed that Roundnose Grenadier will begin to mature at 40-50 cm TL (Atkinson 1995*a*). Bergstad and Isaksen (1987) found that along Norway's coast, males and females reach maturity in 8 and 10 years, respectively.

Fecundity in Roundnose Grenadier is determinate and relatively low: females produce 8,700-56,000 eggs (Alekseyev et al. 1992; Kelly et al. 1997; Lorance et al. 2001*b*; Clarke et al. 2003; Baker et al. 2009). They breed more than once in their lifetimes (iteroparous), have "group-synchronous" ovarian organization (one group of larger oocytes to be spawned in the current breeding season plus another group of small oocytes to be spawned in future seasons), and are

"batch" spawners (releasing eggs in more than one spawning event during each spawning season; Murua and Saborido-Rey 2003).

Exact timing of spawning is unknown. The majority of fish in the Rockall Trough were spent or recovering in April and ripe in September (Kelly et al. 1997). This was interpreted as possible evidence of two spawning events over the year. However, no egg or larval information was available from the area (Kelly et al. 1997). In contrast, some researchers believe spawning occurs from May through September, (peaking sometime in late July or early August: Podrazhanskaya 1971; Cohen et al. 1990), or throughout the year (Lorance et al. 2001*a*). Eggs are fertilized at the time of spawning, are free-floating, spherical; 2.3-2.4 mm in diameter, and contain one oil globule (Grigorev and Serebryakov 1981).

Roundnose Grenadier are long-lived (~60 years: Kelly et al. 1997; Lorance et al. 2001*b*). Otolith data have shown individuals of approximately 90-100 cm in length to be 40 years old, while data from scale-aging methods indicate ages of 10-15 years at 60-80 cm, and 25 years at 95 cm (Atkinson 1995*a*). Average ages of fish caught in the Rockall Trough and Skagerrak were 10-35 years (Kelly et al. 1997) and 18–30 years (Bergstad 1990), respectively. Bergstad (1990) aged Roundnose Grenadiers from the Skagerrak as 1–72 years old; indicating a broad range of age groups present. This species has a long population turnover rate, because it is long-lived, slow-growing, and late to mature. Estimated generation time is 17 years (Lorance et al. 2001*a*); therefore this species is recruited to fisheries before becoming fully mature (Atkinson 1995*a*).

Natural mortality in Roundnose Grenadier has been estimated to be between 0.1 and 0.2 (Bridger 1978; Hoenig 1983; Jensen 1996; Lorance et al. 2001*a*; Clarke et al. 2003). Some researchers believe it to be toward the higher end of the range, and others more toward the lower end. It has been suggested that Roundnose Grenadier is such a long-lived species that its natural mortality would be low. Conversely, they are poor swimmers, and thus vulnerable to predation and targeted or incidental fishing; making natural mortality high.

The number of Roundnose Grenadier populations in the North Atlantic remains undetermined. Grenadiers in the Northeast and Northwest Atlantic may form part of a central spawning concentration along the Reykjanes Ridge (Dushchenko 1988); although this theory has been disputed (Atkinson 1995*b*). Gene frequencies of fish from all areas of the North Atlantic indicated a high degree of homogeneity in muscle enzyme loci (Dushchenko 1988); suggesting hierarchical populations with large scale exchanges of individuals between them. However, this study is unable to explain a low level of homogeneity in muscle enzyme loci in local populations (Kelly et al. 1997).

One hypothesis of a single population suggests that a single stock exists: adults spawning off of Iceland, their eggs and larvae passively distributing throughout the North Atlantic, and mature adults migrating back to Iceland to spawn. However, there is no evidence that Roundnose Grenadiers undertake such large scale migrations; especially given their poor swimming ability. Another theory is that self-sustaining populations are limited to the Mid-Atlantic Ridge and northeastern Atlantic. According to this hypothesis, cooler water in the northwestern Atlantic prevents maturation; so this area represents a population "sink": sustained by the drift of eggs and larvae from other areas. Other theories suggest that local populations occur throughout this species' range, including the Northwest Atlantic. The latter is supported by the occurrence of both early juveniles and mature adults in the Northwest Atlantic, as far south as the Scotian Shelf.

Vinnichenko and Khlivnoy (2008) recently studied the distribution of juvenile Roundnose Grenadier in the North Atlantic. During international trawl-acoustic surveys conducted in 2003 and 2005, data collected on juveniles support the theory of passive drift. Spawning takes place in deep waters around the Mid-Atlantic Ridge, which was suggested as the main spawning area for North Atlantic Roundnose Grenadier. Their free-floating eggs and larvae passively drift with the currents, and are distributed over the North Atlantic. As Grenadiers grow, they begin to migrate to suitable depths along the continental slopes around Canada, Greenland, Iceland, Europe, and around seamounts of the Mid-Atlantic Ridge (ibid). Some juveniles never reach suitable depths and cannot survive as a consequence.

In the absence of data suggesting local adaptation and genetic differentiation for this species in the Northwest Atlantic, this report proposes that Roundnose Grenadiers comprise a single Designatable Unit (DU) in these waters.

CURRENT STATUS

Data Sources

Canadian Research Surveys-Newfoundland and Labrador Region

Fisheries and Oceans Canada has been conducting research surveys in the waters off of Newfoundland and Labrador since 1946 (Templeman 1966). During that period, numerous changes occurred in survey design, research vessels, trawl gear, and area surveyed. Although these research surveys are conducted to monitor resources off of Newfoundland and Labrador, they also extend beyond the Canadian Exclusive Economic Zone (i.e., outside Canada's 200-mile limit; Fig. 2).

In 1946-70, groundfish abundance was estimated using line transect surveys over a range of depths. These Canadian research surveys were conducted in 1946-58 utilizing the *Investigator II* with a Yankee-36 otter trawl. In 1959-70, this vessel was replaced by the *A.T. Cameron* with a Yankee-41.5 otter trawl. In 1971-82, the *A.T. Cameron* was then redeployed annually for new stratified-random surveys in the spring in NAFO Div. 3LNO. This survey design was stratified based on depth to 200 fathoms prior to the early 1990s, with the allocation of sets proportional to the stratum area (Doubleday 1981). In 1984, the *A.T. Cameron* was replaced by the *Alfred Needler*, and the Yankee trawl was replaced with an Engels-145 high-lift otter trawl. In 1986-2005, this spring survey was conducted by the *Wilfred Templeman*. Since then, the *A. Needler*, *W. Templeman*, and *Teleost* were conducting the annual spring survey (with a Campelen-1800 shrimp trawl as of spring 1996).

Canadian spring stratified-random surveys were also conducted in Subdiv. 3Ps and 3Pn since 1972. Survey coverage was relatively constant in recent years; with the exception of 2006, when research vessels' mechanical problems prevented the sampling of Subdiv. 3Ps, and allowed only minimal coverage of Div. 3NO. Essentially, Canadian spring survey indices can be divided into three time series, based on the trawl used: Yankee-36 in 1971-82, Engel-145 in 1983-95, and Campelen-1800 from 1996 to the present. For many fish species, conversion factors were not derived during periods of comparative tows between different survey trawls; therefore these three time series of survey indices must be analysed separately.

Canadian autumn stratified-random research surveys were conducted from 1977 to 1994 in Div. 2J and 1978-94 in Div. 3K by the research vessel *Gadus Atlantica* using an Engel-145 trawl. In Div. 3L, autumn surveys were conducted by the *A.T. Cameron* in 1981-1982, and in

1983-1994 by either the *Alfred Needler* or the *Wilfred Templeman* using an Engel-145 trawl. In autumn 1995, the *Gadus Atlantica* was replaced by the *Teleost*, and Engel-145 trawls were replaced with Campelen-1800 shrimp trawls. In 1995-2009, autumn surveys in NAFO Subareas 2 and 3 were conducted using a Campelen-1800 shrimp trawl by the research vessels *Teleost*, *W. Templeman*, and *A. Needler*.

In 1990, the Canadian autumn research survey was expanded to cover the southern Grand Banks in Div. 3NO. This survey was also expanded into offshore areas of Div. 2J, 3K, and 3L to 1000 m depths (i.e., from the previous 731-m maximum). Furthermore, this survey expanded into both shallower inshore strata and deeper offshore areas in 1995. Throughout the autumn time series, the survey has undergone some variation for different reasons (e.g., vessel mechanical difficulties). Consequently, some years had reduced survey coverage; particularly in deepwater strata. Most notable is the reduced coverage in 2004 and 2006. In addition, NAFO Div. 2G has been excluded from the annual autumn survey, and Div. 2H is sampled only every second year.

To allow for estimates of Canadian abundance and biomass, indices were constructed from the above surveys; including only strata located in Canadian waters. To estimate abundance and biomass over a constant sampling area, only strata sampled throughout the time series were included, and each stratum had to be sampled at least twice a year. Index strata were created for both spring and fall surveys.

Survey sets containing this species were sampled at sea for length by sex in the above autumn surveys of Div. 2J3K, and those samples were used to estimate number at length (STRAP1). Based on the Roundnose Grenadier maturities at length of Bergstad (1990), Canadian estimates were divided into two stages: juveniles <10 cm preanal length (AFL); and adults ≥10 cm AFL. Sexes were combined for this analysis, in order to increase Canadian sample sizes. Note that Campelen survey gear captures a wider range of Grenadier sizes than the Engel trawl; including very small juveniles. Therefore, both time series are not comparable in the absence of any conversion factors for Roundnose Grenadier.

Canadian Research Surveys-Maritimes Region

Fisheries and Oceans Canada has been conducting research vessel (RV) surveys on the Scotian Shelf in NAFO Div. 4VWX+5 since 1970. The longest time series is the summer stratified random bottom trawl survey conducted annually from 1970 to 2009 sampling depths of 50-540 m. These surveys were expanded to include three strata (496, 497, 498) of 450-700 m depths along the shelf edge from 1995 to 2009. Spring and autumn stratified random bottom trawl surveys were conducted from 1978 to 1984 sampling depths of 50-540 m. Since 1984, a spring stratified random survey has been conducted in 4VsW at depths of 50-520 m. Spring surveys of Georges Bank (NAFO Div. 5) have been conducted since 1986, sampling depths of 25-250 m. From 1982 to 1988, annual stratified random bottom surveys were conducted along the edge of the Scotian shelf at 200-900 m depths to assess redfish stocks.

DFO-Industry Collaborative Surveys – Maritimes Region

As a collaborative DFO-Industry project, two exploratory fishing surveys were conducted by the commercial fishing trawler *Cape Chidley* along the slope of the Scotian Shelf in 1994 and 1995 at depths of 914-1829 m. In 1994, four areas were fished: south of Browns, LaHave, Western and Banquereau Banks. In 1995, locations south of Browns, LaHave, Emerald and Western-

Sable Island were fished. Each location was divided into five 183 m depth strata which were sampled with a minimum of two randomly selected tows using an Engel high-lift bottom trawl.

Canadian Research Surveys – Central and Arctic Region

Stratified random otter trawl surveys covering depths 400-1500 m were conducted with an Alfredo-III bottom trawl in NAFO Div. 0A in 1999, 2001, 2004, 2006, and 2008, and in Div. 0B in 2000 and 2001. The 2006 and 2008 surveys included sets in shallow strata (100-800 m) using a Cosmos shrimp trawl. These surveys were conducted by DFO in collaboration with Nunavut partners and the Greenland Institute of Natural Resources. Surveys were carried out with the Greenlandic research vessel *Paamiut*.

Greenlandic Research Surveys

Areas off west Greenland were surveyed in 1987-94 covering NAFO Subareas 1C and 1D at depths of 34 to 1,497 m in waters adjacent to Canadian waters. A Japanese research vessel (*Shinkai Maru*) conducted this survey at various times between April and September, using an otter trawl with a mesh size of 140 mm and a codend liner of 30 mm mesh (Jørgensen 1996). Another series of research surveys was initiated in 1997, covering NAFO Subareas 1C and 1D at 400-1500 m depths. The research trawler used was the *Paamiut*, equipped with an Alfredo-III trawl bearing mesh sizes identical to those used by the *Shinkai Maru* in previous Greenlandic surveys.

Spanish Research Surveys

Waters adjacent to the Canadian EEZ were surveyed by Spain (Instituto Español de Oceanografía, Far Fishery Program Communication), covering the "Nose" and "Tail" of the Grand Banks (NAFO Div. 3L and 3NO) and the Flemish Cap (Div. 3M). Surveys from 1997 to 2001 in Div. 3NO were completed by the Spanish research vessel, *Playa de Menduiña*, with a Pedreira trawl. Research surveys during 2002-2009 in Div. 3NO were conducted using the Spanish *Vizconde de Eza* equipped with a Campelen trawl. This research trawler was also used in Div. 3L for 2003-04 and 2006-09. Surveys were conducted on the Flemish Cap (Div. 3M) during 1992-2003 with the research vessel *Cornide Saavedra* using a Lofoten trawl, and in 2004-09 with the research vessel *Vizconde de Eza* using the same trawl. Conversion factors are not currently available for these different trawls; therefore a comparison between each time series is not possible.

ABUNDANCE

Canadian Research Surveys-Newfoundland and Labrador Region

Spring Surveys

Catches of Roundnose Grenadier in this survey in NAFO Div. 3LNO were sporadic during the Yankee series, and remained so during the Engel series until 1991 (Fig. 3). From 1991 to 1994, catches in Div. 3LNO were very low, but consistent. Following the addition of deepwater strata in 1994, and a gear change to Campelen trawls in 1996, there was an increase in catch rates of Roundnose Grenadier. During the Campelen series, catch rates of this species in Div. 3LNO remain relatively constant at low levels. In Subdiv. 3Ps, catches of Roundnose Grenadier were intermittent and very low throughout this time series (ibid.).

Limiting analysis to only Index strata that were consistently sampled during the spring Campelen series provides a similar indication of consistently low catch rates in Div. 3LNO (Fig. 4). Further limiting analysis to strata which only occur in Canadian waters resulted in an absence of Grenadier catches in Div. 3N; because strata on the Tail of the Grand Bank and along much of the eastern slope (where Roundnose Grenadier occur) are outside Canadian waters. Similarly, some deepwater areas of Div. 3L and 3O were removed from the analysis. In both Div. 3L and 3O, catch rates of Roundnose Grenadier remained low and consistent throughout the Campelen series.

Autumn Surveys

Surveys conducted in NAFO Div. 2J indicated low but steady numbers from 1981 to 1994 (Fig. 5a). Mean number per tow in Div. 2J during 1977-80 averaged 11.9 fish; compared to 1.2 Roundnose Grenadier per tow in 1991-94. Except for a peak of 12.3 fish per tow in 1996, mean number per tow in Div. 2J were relatively stable in 1995-2009; averaging 5.3 fish. Mean number per tow in Div. 3K rapidly declined from 47 to 6.7 fish over 1978-81. For 1986-89, catches of Roundnose Grenadier in Div. 3K were non-existent. Catches with Engel trawls in Div. 3K for 1990-94 remained low; averaging 2.3 fish. In 1995 mean number per tow increased in Div. 3K with the introduction of the Campelen gear (reflecting higher catchability for smaller Grenadier); peaking at 31.4 fish in 1996, then averaging 11.8 Roundnose Grenadiers from 1997-present.

In Div. 3L during the 1980s, mean number per tow of Roundnose Grenadier were very low; averaging 0.3 fish (Fig. 5b). From 1990 to 1994, catch rates in Div. 3L were low with the Engel gear, and remained at low levels after switching to the Campelen gear from 1995 to 2008. For 2009, the catch rate estimated in 3L is significantly higher than in previous time periods. This is consistent with the estimated catch rates in Div. 3NO in 2009. In Div. 3NO, catch rates were low and variable throughout the times series until the most recent estimate. Sampling outside the Canadian EEZ on the Flemish Cap (Div. 3M) occurred in 1996-2003 and 2006-07. Mean number per tow remained high in this area; averaging 89.9 fish, with the largest value observed in 1997 at 220.8 fish per tow.

Limiting analysis to only Index strata (which were sampled throughout Canadian surveys: 1977-2009 in Div. 2J; 1978-2009 in Div. 3K) results in the elimination of Div. 3K as an area containing Roundnose Grenadier. Throughout the time series in Div. 2J, Grenadier mean number per tow were low and variable (averaging 0.2 fish in Engel years, and 0.1 fish in Campelen years; Fig. 6); apparently only higher during the late 1970s (at 1.0 fish in 1979) and 1980 (at 0.6 fish) with Engel trawls. Reanalysis based solely on Campelen data indicated increases in Div. 2J and 3K that peaked in 1996 at 4.09 and 7.03 fish per tow, respectively; then declined with minor variations from 1997 onwards (Fig. 7). Mean number per tow in Div. 2J and 3K increased to averages of 3.7 and 4.4 fish in 2006-07, respectively; subsequently averaging 1.5 and 8.1 fish per tow, respectively, in 2008-09.

Estimates of the abundance of juvenile (<10 cm AFL) and adult Roundnose Grenadier from Canadian autumn surveys in Div. 2J3K indicate significantly decreasing trends in both time series (Fig. 8); albeit not directly comparable due to different gear selectivities: Engel trawl surveys (1978-94) showed a similar rate of decline to very low numbers for both juveniles and adults; Campelen surveys (1995-2009) also indicated a decreasing trend to very low numbers for adults, while juveniles appeared to decline to a moderate level.

Canadian Research Surveys-Maritimes region

Only a few Roundnose Grenadier were caught in the Summer surveys between 1970 and 1994 before sampling was extended to depths >450 m. Catches in the deep strata since 1995 have been erratic, ranging from 0-12 mean number per tow (Fig. 30). Most were juveniles with total lengths <50 cm (Fig. 31).

Catches from the *Cape Chidley* surveys show that Roundnose Grenadier occur deeper than the range of most Maritimes RV surveys (Fig. 32). Highest stratified mean abundances occurred in the 1080-1260 m depth stratum (330 number per standardized tow; 240 kg per standardized tow) followed by 1261-1440 m. The *Cape Chidley* surveys captured a broad range of total lengths with 62 % of the animals >50 cm (Fig. 33).

Canadian Research Surveys – Central and Arctic Region

Estimated biomass and abundance in Div. 0B in 2000 were 1,660 tons and 9.2 x 10^6 fish, respectively. During 2001, biomass and abundance estimates decreased to 1,256 tons and 7.87 x 10^6 fish, respectively. In both survey years, there were no Roundnose Grenadiers caught above 501 m, and catches were observed to increase with increasing depth (Treble et al. 2001, and Treble 2002). A single Roundnose Grenadier was caught by research trawl in Div. 0A during the 1999 survey. No Roundnose Grenadier was caught in subsequent surveys of Div. 0A.

Greenland Research Surveys

Data collected revealed numerous variations in abundance both between and within years. Surveys in 1987 showed an average catch of 7,946 Grenadiers per km²; which significantly decreased to 399 fish per km² by 1994. However it should also be noted that in some years, several seasonal surveys demonstrated similar fluctuations in abundance of Roundnose Grenadier. In 1990, it was observed that abundance increased from 436 Grenadiers per km² in June to 1,865 fish per km² in August-September. During 1992, a decrease from 5,583 Grenadiers per km² in August to 507 fish per km² in November-December was observed. Roundnose Grenadier was also found to be more abundant with increasing depths (Jørgensen 1996). Surveys conducted from 1997-2008 found Roundnose Grenadiers in most areas surveyed, but showed declining catch rates. Biomass estimates in 2008, mostly from Div. 1D, were the lowest ever recorded at 546 tons; down from 838 tons in the previous year (Fig. 9). Abundance estimates were also at their lowest in 2008 at 4.75x10^6 Grenadiers; compared to 13.162x10^6 fish in 2007 (Jørgensen 2009).

Spanish Research Surveys

Spanish research surveys in the NAFO Regulatory Area (NRA) of Div. 3LNO (i.e., outside of Canada's 200-mile limit) during 1997-2001 showed an increase in Grenadier biomass; peaking in 2000 at 5,404 t, then decreasing to 4,344 t in 2001 (Fig. 10). In 2002-09, an increasing trend was observed, with a peak of 2,862 t in 2009. Spanish surveys in Div. 3L over 2003-04 and 2006-09 indicated that Roundnose Grenadier biomass was on an upward trend (averaging 2,003 t); although a slight decrease was noted in 2009 (1,963 t). Surveys on the Flemish Cap (Div. 3M) in 1992-2003 resulted in very low biomass indices. After a research vessel change (using the same type of trawl), higher biomass indices were observed in Div. 3M; averaging 5,485 t for 2004-09, with the highest index at 6,597 t). It should be noted that the survey was

expanded to cover depths up to 1450 m which makes the trends over the entire time period uninformative.

DISTRIBUTION

This species was caught in the Davis Strait, along the continental slope off of Newfoundland and Labrador, along the edge of the Grand Banks, Georges Bank, and Flemish Cap.

Canadian autumn surveys in 1979-1983 showed Roundnose Grenadier were most abundant in deeper waters along the continental slope in NAFO Div. 2GHJ3KL (Fig. 11). Surveys in 1984-1988 displayed a slight increase in distribution along the slope's edge in Div. 2GHJ3K in Canada's EEZ, and in Div. 3L just outside Canada's 200-mile limit. An increase was noted in surveys from 1989-1993 (Fig. 12), due in part to expansion of the survey to Div 3NO in 1990 as well as expanded depth coverage in Div. 3LNO from 367m to 731 m. The most abundant catches occur beyond the slope edge (>367m) in Div. 2HJ3KLNO. For Div. 3LNO most of the abundance occurs outside the 200-mile limit. Trends observed in 1994-1998 had greatly increased over the previous years along the shelf edge. In 1995, both shallow inshore and deeper offshore strata (to 1500 m) were added to the area covered, and, the survey trawl changed from an Engel-145 to a Campelen-1800 shrimp trawl; resulting in different gear selectivities, particularly since the Campelen generally captures a much larger proportion of smaller sized fish. Roundnose Grenadier were found in Div. 2GHJ3KLNO within Canada's 200-mile limit, in Div. 3LM bordering the Flemish Cap, and in Div. 3NO outside Canada's EEZ; remaining on the slope's circumference. The same pattern was seen for surveys in 1999-2003 (Fig.13); with a slight decrease in Div. 2G. during 2004-08. The locations where Roundnose Grenadiers were found remained the same: on the continental slope boarder in Div. 2HJ3KLNO inside Canada's EEZ, in Div. 3LNO outside Canadian waters, and in Div. 3M on the edge of the Flemish Cap.

Canadian spring surveys over 1979-2008 in NAFO Div. 3LNO and Subdiv. 3Ps generated much lower catch rates relative to autumn surveys. However, the spring coverage was only to a maximum of 367 m in Div. 3LNO to 1990 and then only to 731 m in 2008, restricting meaningful comparisons. In 1971-83 (Fig. 14) and 1984-88, little to no catches were observed. Surveys in 1989–93 (Fig. 15) expanded the area and depth surveyed; therefore, an increase in catches was expected. Catches from 1994-1998 were generally higher than the previous five year summary again likely influenced by the change of gear to the Campelen in 1995. The same general distribution pattern of larger catches outside the continental slope was observed in surveys plotted over 1999-2003 (Fig. 16) and 2004-08. Subdiv. 3Ps was not sampled in 2006, and minimal coverage occurred in Div. 3NO because of research vessels' mechanical problems.

Roundnose Grenadier have been captured infrequently during the Summer RV surveys in the Fundian Channel and south of LaHave (4X), Western (4W) and Banquereau Banks (4Vs, Fig. 34). They were also captured occasionally in the autumn and spring RV surveys and Redfish RV surveys (Figs. 35-38), but not in the Georges Bank RV surveys.

The *Cape Chidley* surveys captured Roundnose Grenadier in all locations sampled with the highest catches occurring south of LaHave Bank (Fig 39). Surveys in SA0 indicate Roundnose Grenadier were found at depths below 500 m and were most abundant in Div. 0B at depths greater than 1000 m (Treble et al. 2001, Treble 2002). The northern most catch occurred in Div. 0A at 66° 29' N Latitude (Treble et al. 2000).

AREA OCCUPIED

Data from the Canadian autumn research surveys indicated temporal variation in the area occupied by Roundnose Grenadier in NAFO Div. 2J (Fig. 17). This variation centered on a relatively consistent mean of approximately 4 % of the area surveyed in 1995-2008; perhaps with a slight increase over this time period. Years prior to 1995 (Engel series) showed similar consistencies, but with greater variations. However, conversions from Engel gear data to Campelen estimates are not available for this species. Therefore, as noted previously, observed deviations from the Campelen series may be due to different selectivities between both trawls; rather than representing actual differences in area occupied.

Div. 3K indicated similar trends as those of Div. 2J; though with a slightly higher proportion of area occupied (6-7 %) in 1995-2008. A large deviation in 2005 was not considered to be a result of any real trend in area occupied; but was possibly resulting from sampling issues that year. It also appears that area occupied in both Divisions showed less temporal variations with Campelen gear, as compared to Engel data.

Div. 3LNO had low proportions of area occupied; probably because these contained sampled areas which were not as deep as those sampled in Div. 2J3K. However, it should be noted that an increasing area of occupation in Div. 3O (less than a 1 % variation: ~ 0.2 %-0.7 %) was observed during 1995-2008. In Div. 3L, there was a slight decrease of approximately half a percent (1.6-1.0 %) during the same period.

Canadian spring research surveys in Div. 3LNO indicated the lowest proportions of area occupied by Roundnose Grenadier in any time series; with less temporal variability during the Campelen years (except in Div. 3O; Fig. 18). In Subdiv. 3Ps, area occupied by this species was almost nonexistent during the Engel years, and absent in the Campelen series.

POPULATION SIZE

Considering the depths at which Roundnose Grenadier are found, many of the Canadian research surveys have been too shallow to provide a good indication of abundance trends. None of the existing surveys cover the spatial extent of this population.

Although the DFO autumn Labrador and north eastern Newfoundland (Div. 2J3K) surveys may sample only a portion of the Roundnose Grenadier distribution, they provide "best" estimates of abundance. Note that, due to a survey gear change in 1995 plus the lack of a length-based conversion factor for this species, it is difficult to compare pre-1994 indices to post-1995 estimates. Furthermore, this index may also be biased because of a size-sex segregation of Roundnose Grenadier (i.e., smaller fish being more abundant in shallower water).

Catch rates of adults in the Canadian autumn surveys of Div. 2J3K were previously reported to decline by 96 % from 1978 to 1994 (COSEWIC 2008). This is consistent with the rate of decline observed in the Index strata for Div. 2J from 1977 to 1994. However, recent trends in abundance in Div. 2J3K from 1995-2009 indicate that catch rates are potentially increasing. This is consistent with the trends in abundance observed outside Canada's EEZ in Div. 3LNO.

PROTECTION/OWNERSHIP

Fisheries management responsibilities off of eastern Canada were moved from the Northwest Atlantic Fisheries Organization to Canada and Denmark (on behalf of Greenland) for northern

waters (NAFO Subareas 0+1), and solely to Canada for more southerly waters (NAFO Subareas 2+3) in 1979, following the extension of Canada's marine economic jurisdiction from 12 nautical miles to 200 (Atkinson 1995*a*). The range of Roundnose Grenadier extends beyond the 200-mile limit of Canada's EEZ boundaries, and it is thus a straddling species.

POPULATION MODELS

Bayesian analysis of Biomass Trends

Population dynamics of Roundnose Grenadier were modeled using Bayesian state-space implementation of the Schaefer Surplus Production (SP) model for NAFO Subareas 2+3 from 1967 to 2009.

In a SP model, the parameters for recruitment, growth, and natural mortality are combined in the single parameter *r*: the intrinsic rate of population growth. The Schaefer (Schaefer 1954) form of a surplus production model is:

$$P_t=[P_{t-1}+ r^*P_{t-1} (1 - P_{t-1}/K)- C_{t-1}]^*\eta_t$$

where P_{t-1} and C_{t-1} denote exploitable biomass and total catch, respectively, for year *t-1*. Carrying capacity, *K*, is the level of stock biomass at equilibrium prior to commencement of a fishery, *r* is the intrinsic rate of population growth, and η_t is a log-normal random variable, $\eta_t \sim LN(0, \sigma^2)$, describing stochasticity in the population dynamics.

An observation equation is used to relate the unobserved (population) biomass, P_t, to the observations (biomass index), I_t.

$$I_t=q^* P_t$$

where q is the catchability parameter and P_t is an estimate of biomass at time t.

Models were run using data proportional to an estimate of K. See, for example, Meyer and Millar (1999*a*, 1999*b*) for a complete description of the SP model.

In Bayesian modeling, each posterior probability is conditioned on the data, where probability, $P(SP_i \mid Dataset)$, is interpreted as a measure of the credibility for SP_i, the unique vector of values of *i*, given the data used.

The model incorporates total catch (directed + bycatch); an index of stock biomass estimated from Canadian research vessel autumn surveys; and separate commercial catch per unit effort indices, one based on data from NAFO, and one from Canadian Fisheries Observers (Table 2); along with several error terms for observed and process-errors. Biomass was modeled historically using estimated priors for K (carrying capacity), r (intrinsic rate of population growth), and q (catchability coefficient; Table 3). Models were examined for convergence and population parameters were forecast 20 years forward using several levels of constant bycatch (0, 0.5, 1.0, 1.25, 1.5, and 3.0 kt·year-1). A projection period of 20 years was chosen since 100 % of Roundnose Grenadier are estimated to be mature by this time, covering one generation. Each scenario, SPi, where i =model number, represents a plausible state of nature or a potential realization of all possible nodes. The following levels of catch were used in each SP model, SPi (assumed here to be bycatch since there are no directed fisheries for Roundnose Grenadier in the NW Atlantic):

1. Bycatch fixed at $SP_{1,t}$ = 0.0 kt·year^{-1}
2. Bycatch fixed at $SP_{2,t}$ = 0.5 kt·year^{-1}
3. Bycatch fixed at $SP_{3,t}$ = 1.0 kt·year^{-1}
4. Bycatch fixed at $SP_{4,t}$ = 1.25 kt·year^{-1}
5. Bycatch fixed at $SP_{5,t}$ = 1.5 kt·year^{-1}
6. Bycatch fixed at $SP_{1,t}$ = 3.0 kt·year^{-1}

The freely available software, WinBUGS (v.1.4.3), was used for all Bayesian Markov Chain Monte Carlo (MCMC) with Gibbs sampling models and these were run using 60000 iterations for each SP_i. Models used a burn-in period of 20000 iterations and were trimmed at 10 to reduce autocorrelation. Posterior estimates were obtained using WinBUGS while projections were run in R (R Project for Statistical Computing, v.2.9.1) using these posteriors (see Appendix 1 for WinBUGS code).

Prior Distributions

Life history, population dynamics, and the catchability of Grenadier in the research surveys are poorly known. Consequently, it is difficult to formulate informative priors for catchability (q), carrying capacity (K), or process-error parameters. Priors for observation error were limited to a lower bound equal to the coefficient of variation (CV) of each index. The upper bound was set at 3 times this CV. The priors used for fitting the model are summarized in Table 3. The prior for r was based on published estimates for this species (Bergstad 1990; Baker et al. 2009). A lognormal distribution was used for this prior.

Typically, K is set to the stock biomass in the year prior to the onset of fishing (P0: Meyer and Millar 1999b). A lognormal distribution for K was specified here with μ=150, std=200. The mean was estimated at three times the maximum stock estimation over the entire time series. The flat distribution with wide upper and lower boundaries was established to encompass well beyond this estimate; in order to reduce the possibility of limiting K to an erroneously low level. Although this prior contained an estimate for the value of K, it was also limited such that the parameter could remain biologically plausible; while covering a broad range of possible values.

Modeling and forecasting population trends

Population dynamics of Roundnose Grenadier were modeled using Bayesian state-space implementation of the Schaefer Surplus Production (SP) model for NAFO Subareas 2+3 in 1967-2009. The model was fit using WinBUGS, and posteriors were transferred to R for projection using various levels of catch. A range of bycatch levels were utilized in the simulations; such that contrasts in projections could be readily observed. Posterior distributions and a summary of the values are shown in Fig. 19a and b) and Table 4. Model fit to the four indices and biomass estimations are shown in Figs. 20 and 21, respectively.

In the models forecast to 2029 (20 years forward), bycatch levels above 1.25 kt·year-1 resulted in a decrease in population biomass over time; eventually decreasing the population to near 0 (Figs. 22 and 23). All rates of bycatch set from 0.0-1.0 kt·year-1 (SPi=1- 3) showed increases in

biomass over time, with no indications of eventual decrease. At 1.25 kt·year-1, biomass was maintained at a consistently low level throughout the 20-year projection; giving no indication of an increase or a decline. At 1.5 kt·year-1, the rate of population decline increased and, at 3.0 kt·year-1, this decline was relatively rapid (ibid.). Figure 24 provides a 3D representation of the effect of various catch levels on Grenadier biomass over the 20-year projection period.

Mean bycatch for the period since the beginning of the Grenadier-directed fishery moratorium in Canada's EEZ (1997-present) was 1.66 kt·year-1. Based on these results, no increase in biomass was expected during this period. For seven of the thirteen years during this moratorium, bycatch levels were below 1 kt·year-1. According to the model, these levels would promote population recovery. However, in 2001-06, bycatch levels averaged 3.44 kt·year-1. This level of Roundnose Grenadier bycatch has likely limited the recovery potential of this species.

It should be noted that 95 % credible intervals increase dramatically as the model approaches forward projections of 20 years, and thus these simulations should be accepted as guidelines only. Indeed, mean bycatch levels over the past 20 years have been at a level (1.66 kt·year-1) predicted to result in eventual population decline. Credible intervals remain relatively narrow when modeling the data, but grow wider where no data are available; creating more uncertainty. This applies to model projections; thus care should be taken when interpreting these results. It should also be pointed out that credible intervals are not interpreted in the same way as confidence intervals. A credible interval can be directly interpreted as the region within which the actual parameter is likely to be found. For example, a 95 % credible interval means that one can be 95 % certain that the actual value lies within the range given.

FISHERY REMOVALS

COMMERCIAL FISHERIES

Commercial fisheries data were obtained from three sources. The first source was the STATLANT-21A database maintained by the Northwest Atlantic Fisheries Organization for use by NAFO member countries. This database contains commercial catches from outside Canada's 200-mile limit; as reported by member countries (including Canada). The latter was used here to estimate non-Canadian removals of Grenadier in 1960-2008, and Canadian catches for 1960-84. The second source was the DFO Zonal Interchange Format (ZIF) database, which was created in 1985 to contain Canadian landings data (recorded in fishers' logbooks and on fish plants' purchase slips) in a standardized electronic format for use amongst DFO regions. The third source was the DFO Observer Program - Science database, which contains set-by-set information collected at sea in a standardized format by trained Canadian Fisheries Observers since 1978. This database was used here to investigate commercial discards of Grenadiers at sea during 1985-2008 (i.e., such data are absent in NAFO-reported catches and ZIF-recorded landings). Commercial landings data for NAFO Divisions 4VWX were also extracted from ZIF and MARFIS databases. Locations of commercial catches were obtained from the Maritimes Observer Database.

NAFO reported catches of this species outside Canada's 200-mile limit in 1967-2008 indicate that the majority of Roundnose Grenadier catches were consistently reported from Div. 3K: averaging 16,912 t in 1967-78, and 4,386 t in 1981-89 (Fig. 25). An exception was for Area 2 in 1971, where total reported catch of all countries was 56,998 t. After Div. 3K, Subareas 2, 1 and 0 generally showed the most significant catches in 1967-83; averaging 7,241 t, 3,849 t, and

2,630 t, respectively. Decreasing trends from high catches reported in Subarea 0, Areas 1+2, and Div. 3K were observed after 1975. NAFO reported catches in the NRA of Subarea 2 and Div. 3K became insignificant in 1994. Div. 3LMN showed two periods of substantial catches later in this time series: averaging 962 t in 1992-95, and 1,288 t in 2001-05. It should be noted that there have been issues of misreporting between Roundnose Grenadier and roughhead Grenadier (*Macrourus berglax*) primarily from fleets fishing in the NAFO Regulatory Area. The catch estimates used in the analyses in this document has taken account of this misreporting where identified (see Power 1999).

Based on ZIF (Zonal Interchange Format) commercial landings for 1985-2008, Canadian reported landings of Roundnose Grenadier inside Canada's 200-mile limit in NAFO Div. 2GHJ3KLNOP averaged 229 tonnes in 1990-95 (Fig. 26), with a peak of 497 t in 1992. Landings in all Divisions declined to zero after 1997. Canadian landings from Div. 3K in 1989-95 averaged 101 t, while average landings from Area 2 in 1990-95 and Div. 3L in 1990-1993 were the same at 62 t. Reported landings from Div. 3NOP were insignificant during this time period.

With respect to fishing gear used by Canadian fishers within Canada's EEZ, ZIF data indicate that Roundnose Grenadier was caught primarily by otter trawls in 1986-97: reported landings averaged 295 t, with a peak of 1,261 t in 1993 (Fig. 27). Gillnet landings averaged 66 t in 1990-96, then fell to zero after 1997. Roundnose Grenadier landings from all gears became insignificant in 1998 and remained so thereafter. Longlines rarely caught this species during this time period. In addition, Roundnose Grenadier was usually taken as bycatch by other Canadian fisheries in Div. 2GHJ3KLNOP (Fig. 28) in 1987-96: reported bycatch landings averaged 166 t, with a peak of 586 t in 1992. Canadian directed fisheries for this species were almost nonexistent; averaging 6 t in 1990-91.

Canadian Fisheries Observers data for 1985-2008 indicate that discards of Roundnose Grenadier observed aboard Canadian vessels within Canada's EEZ were very small; averaging 26 t during this period (Fig. 29). In addition, observed catches of this species by other countries fishing inside Canada's 200-mile limit averaged 2,394 t in 1985-89; then declined to zero by 1994.

There was a commercial fishery for Roundnose Grenadier in the Maritimes Region from 1993 to 1997. The fishery was concentrated in an area south of LaHave Bank (Fig. 40) at an average depth of 1150 m. The highest reported annual landings were 983 mt in 1993 (Table 5). Since 1998, Roundnose Grenadier bycatch has averaged 0.3 mt per year.

DISCUSSION AND CONCLUSIONS

Catch rates of Roundnose Grenadier have shown recent increases, based on Canadian research vessel survey data. This may represent recent increases in abundance, or a shift in distribution, or increases in catchability of this species. There has been no directed fishery for this species in Canada's EEZ since 1997. Therefore, the current level of human-induced mortality can be attributed to commercial bycatch in other directed fisheries (primarily Greenland Halibut). Reported bycatch levels were relatively low for some years; with a subsequent period of higher levels in 2001-06. The surplus production model indicated that, at the mean level of bycatch (1.66 $kt \cdot year^{-1}$) since the moratorium on this species, increases in the Roundnose Grenadier population would not be expected. However, bycatch is currently at a level where slow declines in biomass are predicted to occur.

It has been stated that Roundnose Grenadier has an average maturation age of 10 years; with 100 % maturity estimated at approximately 16-17 years. Baker et al. (2009) used life history characteristics of Roundnose Grenadier to estimate time to recovery under low bycatch rates, and found recovery times to be between 16 and 136 years. Given the relatively short time since the termination of its directed fishery, and the ongoing bycatch of this species, recovery may be proceeding very slowly; or not at all. Deep-sea species do not respond as quickly to disturbances as some pelagic or shelf species can (Jørgensen 2002). In fact, the survey time scale is often such that research had hardly commenced before a directed fishery on deep-sea species had already peaked and collapsed (Atkinson 1985; Haedrich et al. 2001; Devine and Haedrich 2008). Model projections presented here indicated slow recovery with the current bycatch levels of less than 400 t. Keeping commercial bycatch levels consistently low and closely monitoring abundance and biomass, as well as bycatch of Roundnose Grenadier, over the next 5-10 years, will reveal whether this species can undergo slow recovery; as predicted by this model.

SOURCES OF UNCERTAINTY

Roundnose Grenadier is a deep-water species. Consequently, data on its habitat requirements, life history, behaviour, nutritional requirements (etc.) are limited or nonexistent. Human impacts on many of these parameters are not known.

Canadian research vessels do not survey all depths where this species lives (bottom trawl survey covers to a maximum of 1,500 m whereas Roundnose Grenadier occupy depths down to at least 2,500 m (Konstantinov 1980). Therefore, population size likely has been underestimated but more importantly, trends observed in the surveyed area may not reflect trends in the whole population. In addition, there was evidence of some misidentification of catches of this species in the past: Roundnose Grenadier being identified and reported as Roughhead Grenadier (*Macrourus berglax*), and *vice versa* (Power 1999; Kulka et al. 2002).

Modelling biomass projections depends heavily on accurate reporting of catches and discards by commercial fishers. In Canadian waters, however, generally only fish products landed for purchase are recorded in logbooks by fishers; with discarding going unreported. In the NAFO Regulatory Area (outside of Canada's 200-mile limit), non-Canadian vessels prosecute fisheries often without reporting discards. Therefore, it is probable that levels of Roundnose Grenadier bycatch are underestimated (or possibly identified incorrectly at sea). Considering current socio-economic constraints, any reductions in commercial bycatch of Roundnose Grenadier in other directed fisheries may prove crucial to the recovery of this population.

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Table 1. Conversion equations for pre-anal fin length (AFL) to total length (TL), AFL to anal fin length (AL), and several length-weight relationships for fresh (f), iced (ice), and frozen (fz) Roundnose Grenadier (adapted from Kelly et al. 1997).

Conversion	Equation	Source
Pre-Anal Fin Length to Total Length	TL=4.48· AFL+0.76	Kelley et al. 1997
Pre-Anal Fin Length to Total Length	TL=4.16 ·AFL+0.75	Bergstad 1990
Pre-Anal Fin Length to Anal Fin Length	AL=1.063· AFL-0.38	Atkinson 1981
Length-Weight (Fresh)	$W_f=0.732(L^{2.587})$	Kelley et al. 1997
Length-Weight (Iced)	$W_{ice}=2.287(L^{2.176})$	Kelley et al. 1997
Length-Weight (Frozen)	$W_{fz}=1.652(L^{2.274})$	Kelley et al. 1997
Iced Weight to Fresh Weight	$Ln(W_f)=1.035(LnW_{ice})-0.06$	Kelley et al. 1997
Frozen Weight to Fresh Weight	$Ln(W_f)=0.991(LnW_{fz})+0.211$	Kelley et al. 1997

Table 2. Data used in the surplus production model for Roundnose Grenadier: DFO research vessel (RV) autumn survey estimated biomass (NAFO Division 2J3KL), NAFO reported commercial and Canadian Fisheries Observers commercial catch per unit effort.

Year	RV Surveys (Engel Trawl)	RV Surveys (Campelen Trawl)	NAFO CPUE Series	Canadian Observers Series (CPUE)	Catch (tons)
1967	NA	NA	1.73	NA	17.094
1968	NA	NA	1.85	NA	30.657
1969	NA	NA	2.14	NA	12.333
1970	NA	NA	2.45	NA	22.735
1971	NA	NA	1.84	NA	75.39
1972	NA	NA	1.61	NA	24.231
1973	NA	NA	2.36	NA	17.399
1974	NA	NA	2.29	NA	28.376
1975	NA	NA	2.285	NA	27.167
1976	NA	NA	1.52	NA	20.318
1977	NA	NA	1.51	NA	15.386
1978	48.244	NA	1.515	0.775	20.702
1979	35.498	NA	1.04	0.837	7.781
1980	35.781	NA	1.3	1.1	2.053
1981	6.974	NA	1	0.975	7.085
1982	5.858	NA	0.98	1	4.344
1983	9.55	NA	0.93	0.725	3.569
1984	12.999	NA	1.11	1.53	3.873
1985	14.258	NA	0.84	0.832	4.948
1986	2.639	NA	0.943	0.967	7.427
1987	0.724	NA	0.78	1.1	7.297
1988	1.337	NA	0.73	0.82	5.382
1989	1.065	NA	0.62	0.71	4.666
1990	4.142	NA	0.674	0.62	0.819
1991	3.21	NA	NA	0.355	0.466
1992	0.244	NA	NA	NA	1.378
1993	1.179	NA	NA	NA	0.406
1994	0.578	NA	NA	NA	0.114
1995	NA	11.497	NA	NA	0.229
1996	NA	33.499	NA	NA	0.363
1997	NA	18.056	NA	NA	0.049
1998	NA	14.04	NA	NA	0.037
1999	NA	10.093	NA	NA	0.092
2000	NA	11.059	NA	NA	0.063
2001	NA	7.807	NA	NA	5.435
2002	NA	6.948	NA	NA	4.884
2003	NA	5.26	NA	NA	3.768
2004	NA	10.99	NA	NA	2.802
2005	NA	4.381	NA	NA	2.542
2006	NA	6.351	NA	NA	1.18
2007	NA	7.811	NA	NA	0.375
2008	NA	4.115	NA	NA	0.333
2009	NA	6.095	NA	NA	

Table 3. Prior probability density functions for parameters of the surplus production model for Roundnose Grenadier.

Parameter	Prior
r	LN(-1.093,4.03)I(0.001,1.5)
q.e	U(0,2)
q.c	U(0,2)
q.nafo	U(0,2)
q.obs	U(0,2)
K	LN(5.01,10.6)
σ	U(0, 10)
t.e	U(1.31, 3.92)
t.c	U(0. 70, 2.11)
t.nafo	U(0.416, 1.25)
t.cpue	U(0.309, 0.92)
x	U(0, 2)
y	U(0, 2)

Table 4. Surplus production model results for DFO research vessel (RV) autumn survey estimated biomass (NAFO Division. 2J3KL), NAFO reported commercial and Canadian Fisheries Observers (CanObs) commercial catch per unit effort. Values are medians and 95% credible intervals. K =carrying capacity (000s tons); r =intrinsic rate of population growth; q.e =estimated catchability for the RV Engel series (1978-94); q.c =estimated catchability for the RV Campelen series (1995-2009); q.nafo =estimated catchability for the NAFO series (1967-90); q.obs =estimated catchability for the Canadian Observers series (1978-91); x and y are exponents added to the commercial series (NAFO and CanObs) to allow for directed fishery effort; the deviance is a measure of model fit.

Parameter	0.025	Median	0.975
r	0.0895	0.1815	0.3427
K	121.80	202.25	296.70
q.e	0.0774	0.2382	0.6680
q.c	0.2269	0.8333	1.7580
q.nafo	0.0069	0.0109	0.0176
q.obs	0.0046	0.0103	0.0367
deviance	212.4	223.9	240.1
x	0.0762	0.4032	1.037
y	0.2109	0.3978	0.6797

Table 5. Commercial landings (mt) of Roundnose Grenadier reported from NAFO Divisions 4VWX from 1987 to 2009.

	Landings (mt)				
Year	4Vn	4Vs	4W	4X	Total
1987		0.23			0.23
1988	0.06				0.06
1989		0.02			0.02
1991			0.32		0.32
1992			0.01		0.01
1993	0.10	0.11	2.26	980.54	983.01
1994	0.28	0.37	58.75	384.01	443.41
1995	0.00	0.07	71.64	561.14	632.85
1996		0.00	2.34	200.93	203.27
1997		0.01	2.77	65.48	68.27
1998		0.08	0.02		0.10
1999		0.00			0.00
2000			0.02	0.30	0.32
2001		0.07	0.02	1.28	1.37
2002		0.18	0.05	0.01	0.24
2003		0.63	0.09	0.09	0.81
2004		0.15	0.07		0.22
2005		0.12	0.11	0.00	0.23
2006			0.04	0.02	0.06
2007		0.04	0.09		0.14
2008		0.02	0.02		0.04
2009		0.00	0.00		0.00

(G.Taylor 2009)

Figure 1. Roundnose Grenadier, Coryphaenoides rupestris (Gunnerus, 1765).

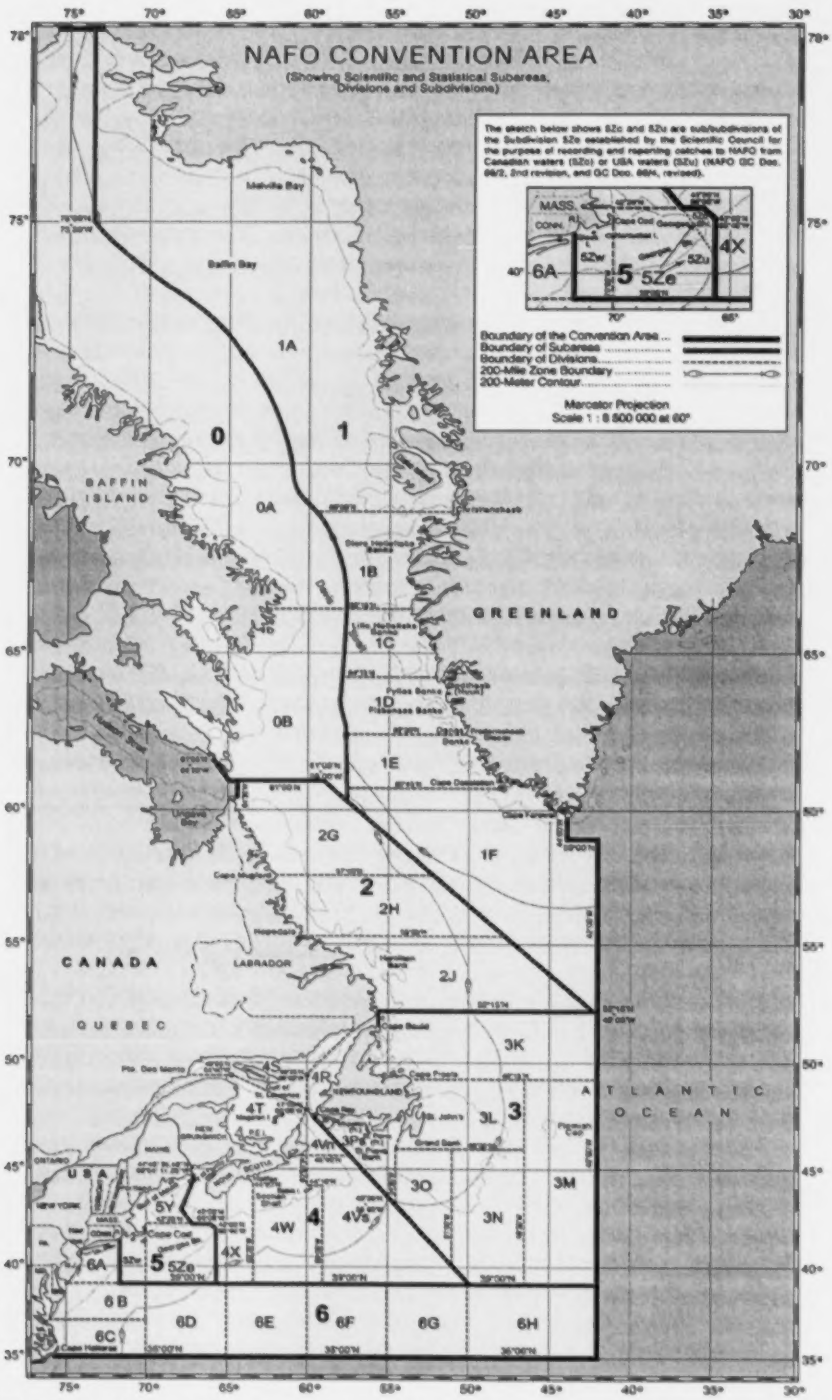

Figure 2. Map of NAFO Divisions (red lines) in relation to Canada's 200-mile limit (blue fish line delineating Canadian territory from the NAFO Regulatory Area).

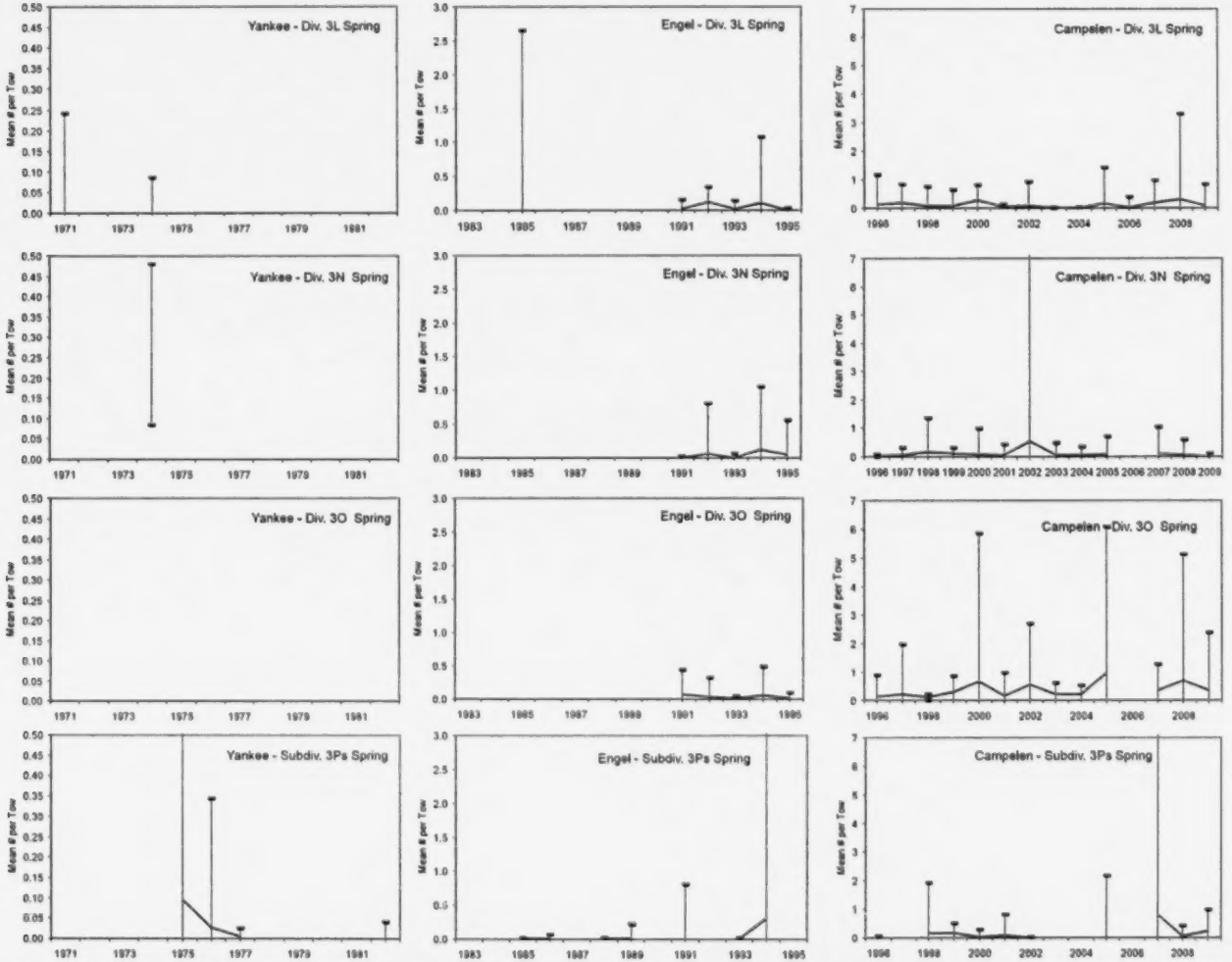
Yankee - Div. 3L Spring
Engel - Div. 3L Spring
Campelen - Div. 3L Spring
Yankee - Div. 3N Spring
Engel - Div. 3N Spring
Campelen - Div. 3N Spring
Yankee - Div. 3O Spring
Engel - Div. 3O Spring
Campelen - Div. 3O Spring
Yankee - Subdiv. 3Ps Spring
Engel - Subdiv. 3Ps Spring
Campelen - Subdiv. 3Ps Spring
Mean # per Tow

Figure 3. Mean number per tow of Roundnose Grenadier from Canadian spring research surveys of all strata in NAFO Divisions 3LNOPs, 1971-2009. Yankee, Engel, and Campelen time series are not standardized. Vertical bars represent 95 % confidence intervals. Note that deep strata in Division 3NO and all of Subdivision 3Ps were not surveyed in spring 2006.

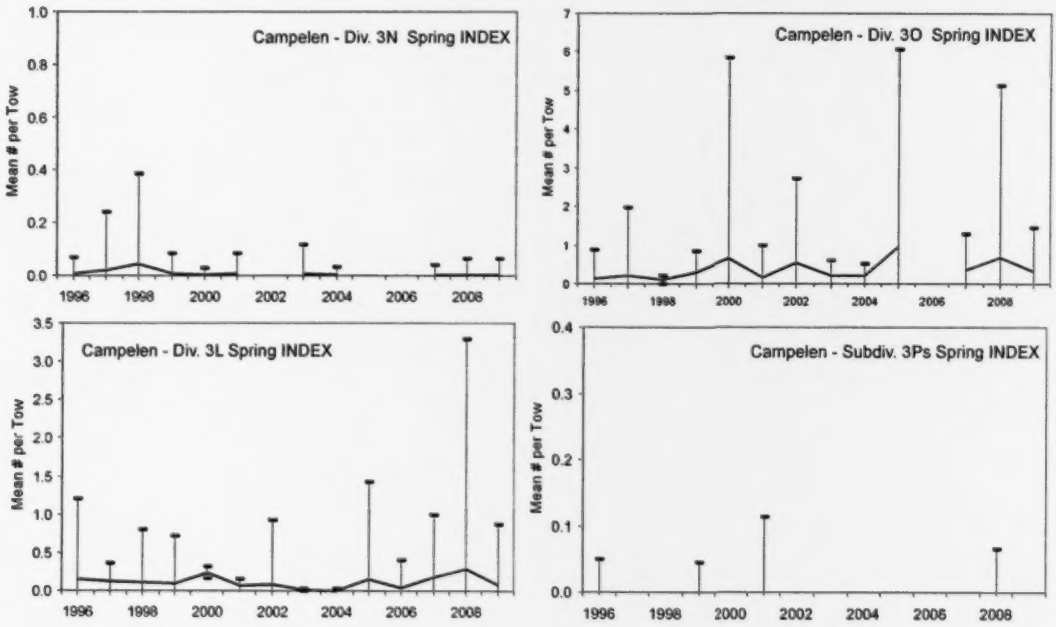

Figure 4. Mean number per tow of Roundnose Grenadier from Canadian spring research surveys of INDEX strata in NAFO Divisions 3LNOPs, 1996-2009. Vertical bars represent 95 % confidence intervals. Note that deep strata in Division 3NO and all of Subdivision 3Ps were not surveyed in spring 2006.

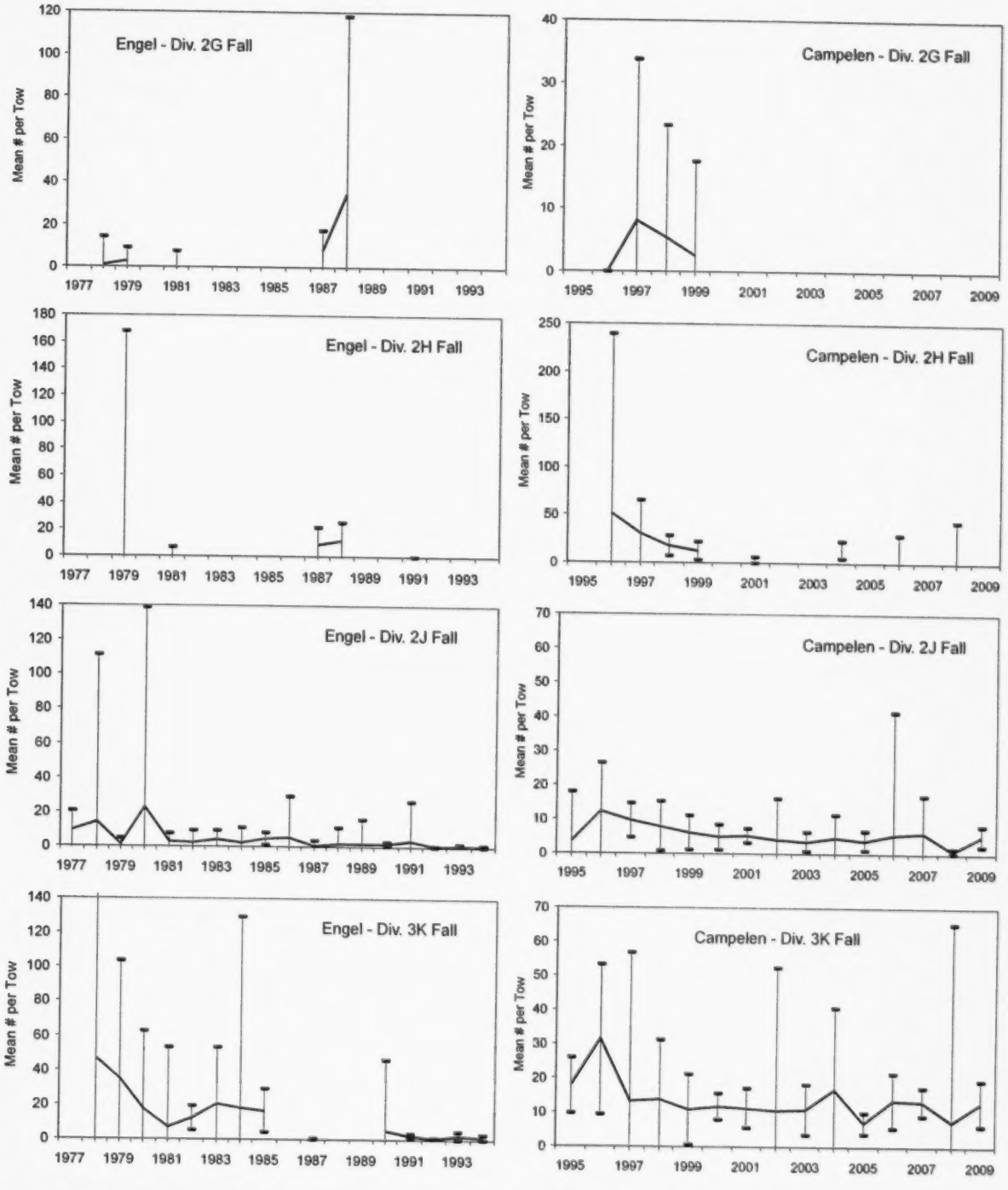
Engel - Div. 2G Fall
Campelen - Div. 2G Fall
Engel - Div. 2H Fall
Campelen - Div. 2H Fall
Engel - Div. 2J Fall
Campelen - Div. 2J Fall
Engel - Div. 3K Fall
Campelen - Div. 3K Fall
Mean # per Tow

Figure 5a. Mean number per tow of Roundnose Grenadier from Canadian autumn research surveys of all strata in NAFO Divisions 2GHJ3K, 1977-2009. Engel and Campelen time series are not standardized. Vertical bars represent 95% confidence intervals.

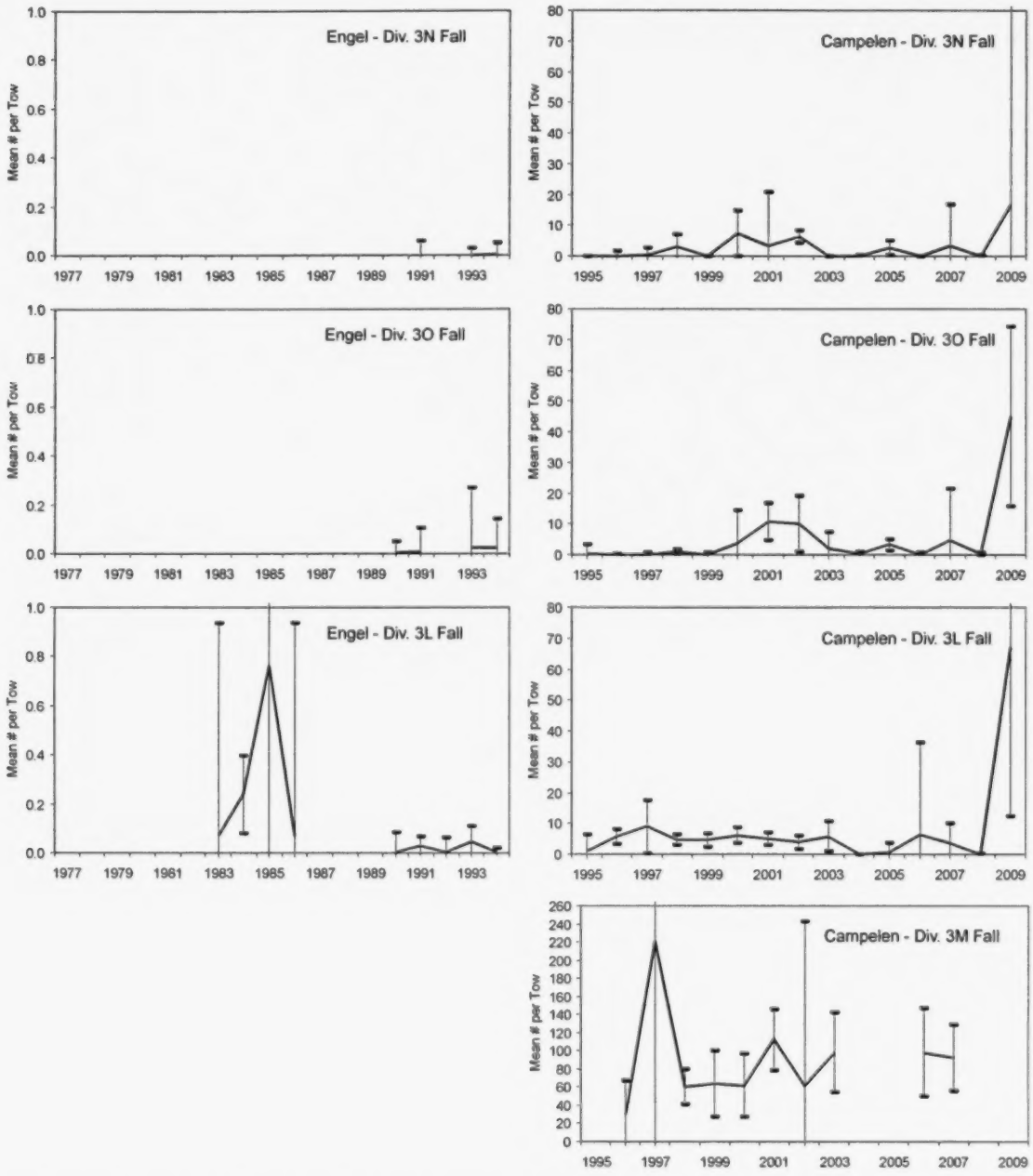
Engel - Div. 3N Fall
Campelen - Div. 3N Fall
Engel - Div. 3O Fall
Campelen - Div. 3O Fall
Engel - Div. 3L Fall
Campelen - Div. 3L Fall
Campelen - Div. 3M Fall
Mean # per Tow

Figure 5b. Mean number per tow of Roundnose Grenadier from Canadian autumn research surveys of all strata in NAFO Divisions 3LMNO, 1983-2009. Engel and Campelen time series are not standardized. Vertical bars represent 95 % confidence intervals. Note that deep strata in Division 3NO were not surveyed in autumn of 2003, 2004, 2006, and strata deeper than 730 m in the survey area were not surveyed in autumn 2008; due to Canadian research vessels' mechanical difficulties.

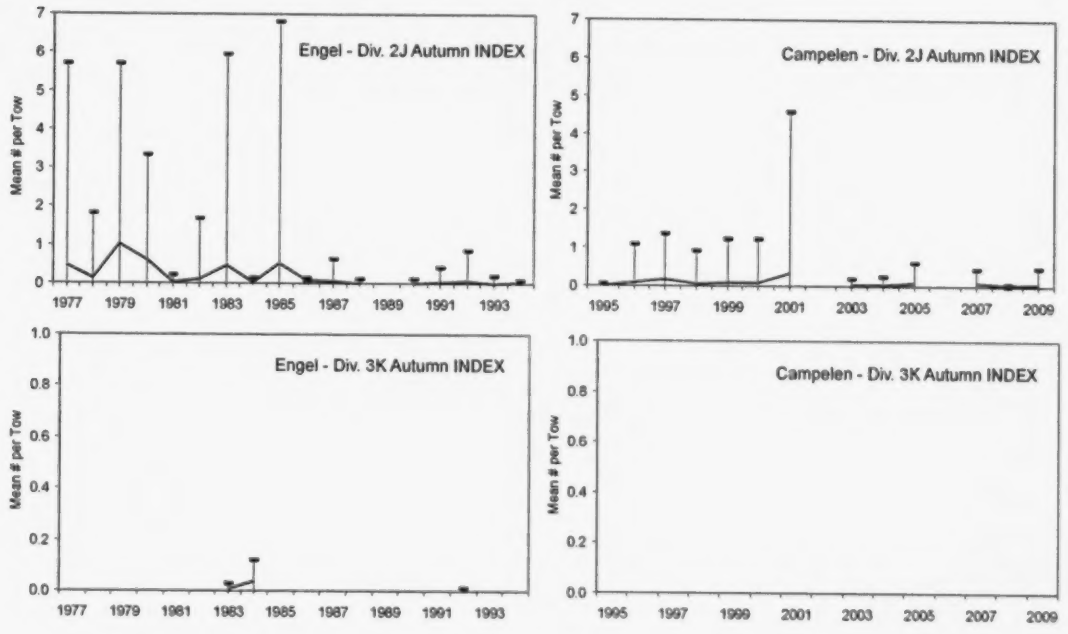
Engel - Div. 2J Autumn INDEX
Campelen - Div. 2J Autumn INDEX
Engel - Div. 3K Autumn INDEX
Campelen - Div. 3K Autumn INDEX
Mean # per Tow

Figure 6. Mean number per tow of Roundnose Grenadier from Canadian autumn research surveys of INDEX strata in NAFO Divisions 2J3K, 1977-2009. Engel and Campelen time series are not standardized. Vertical bars represent 95 % confidence intervals.

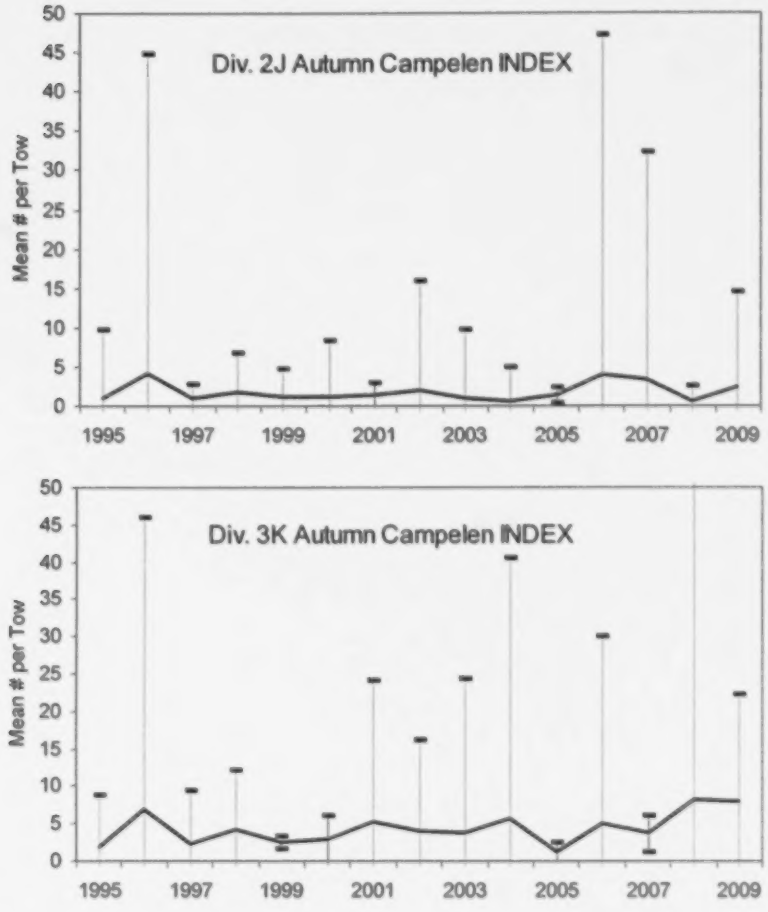

Figure 7. Mean number per tow of Roundnose Grenadier from Canadian Campelen autumn research surveys of INDEX strata in NAFO Divisions 2J3K, 1995-2009. Vertical bars represent 95 % confidence intervals.

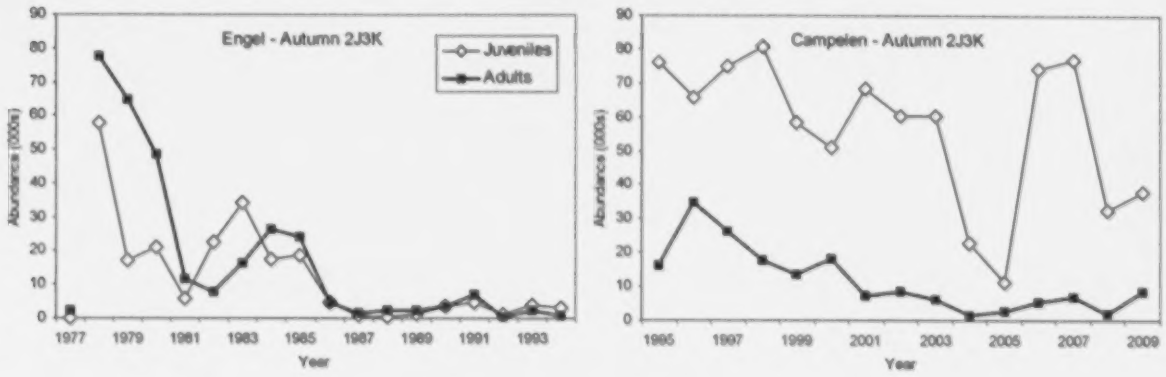

Figure 8. Estimated number of juvenile and adult Roundnose Grenadiers (STRAP1 abundance-at-length; juveniles <10 cm PAL) from Canadian autumn research surveys of Division 2J3K, 1977-2009. Engel and Campelen time series are not standardized. All strata were included in estimates.

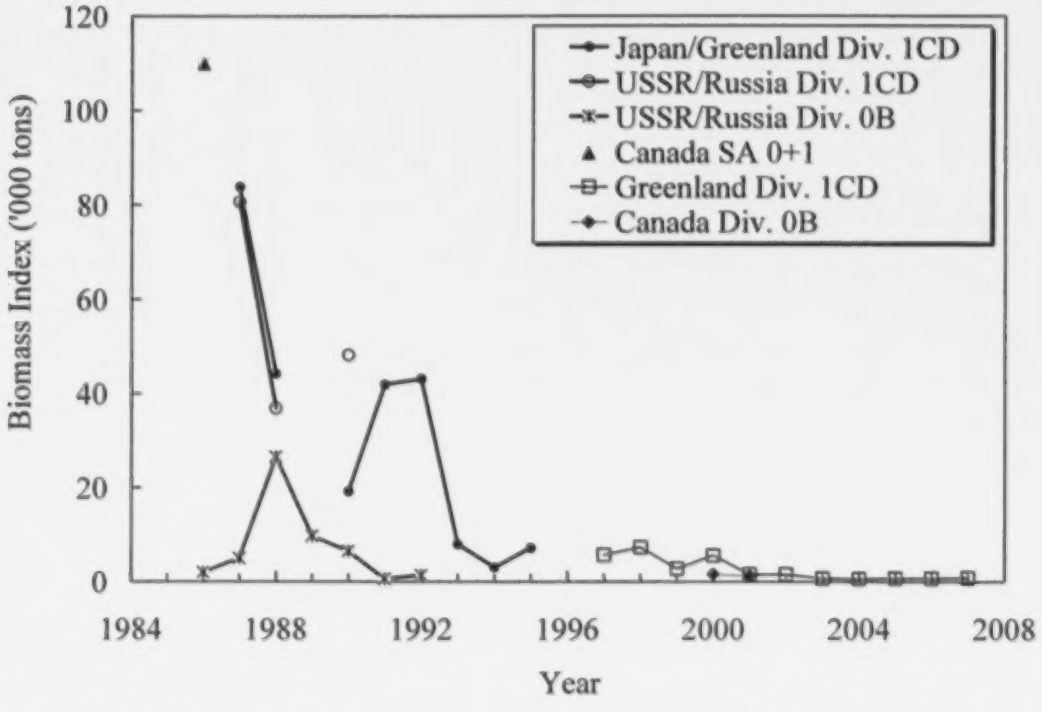

Figure 9. Biomass indices from various research surveys in Subareas 0 and 1, 1986-2007 (Jorgenson, 2009).

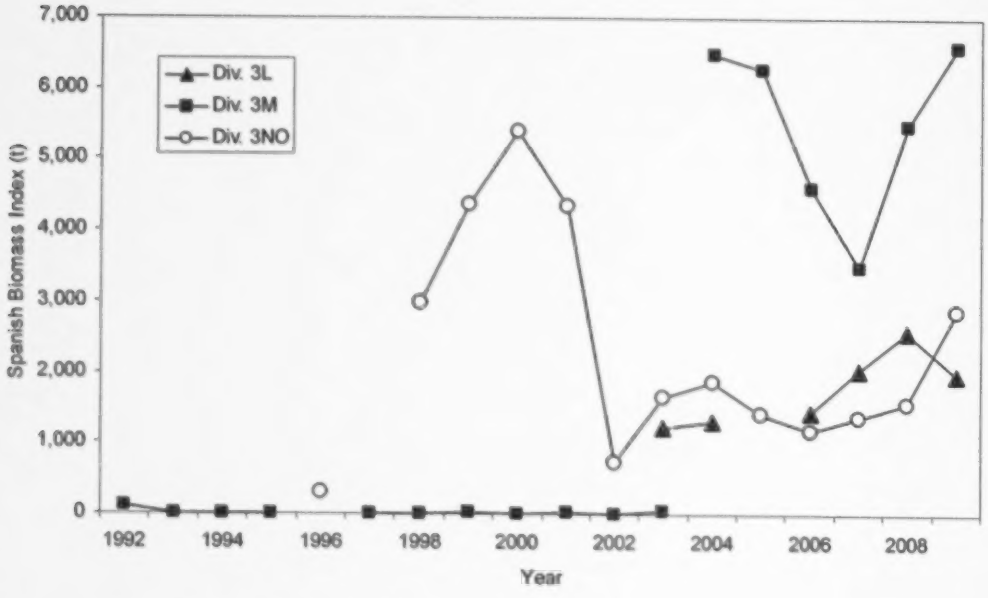

Figure 10. Biomass indices from Spanish research surveys in Divisions 3L, 3M, and 3NO, 1992-2009. Note that Spanish surveys occur only in the NAFO Regulatory Area of Division 3LNO (outside of Canada's 200-mile limit).

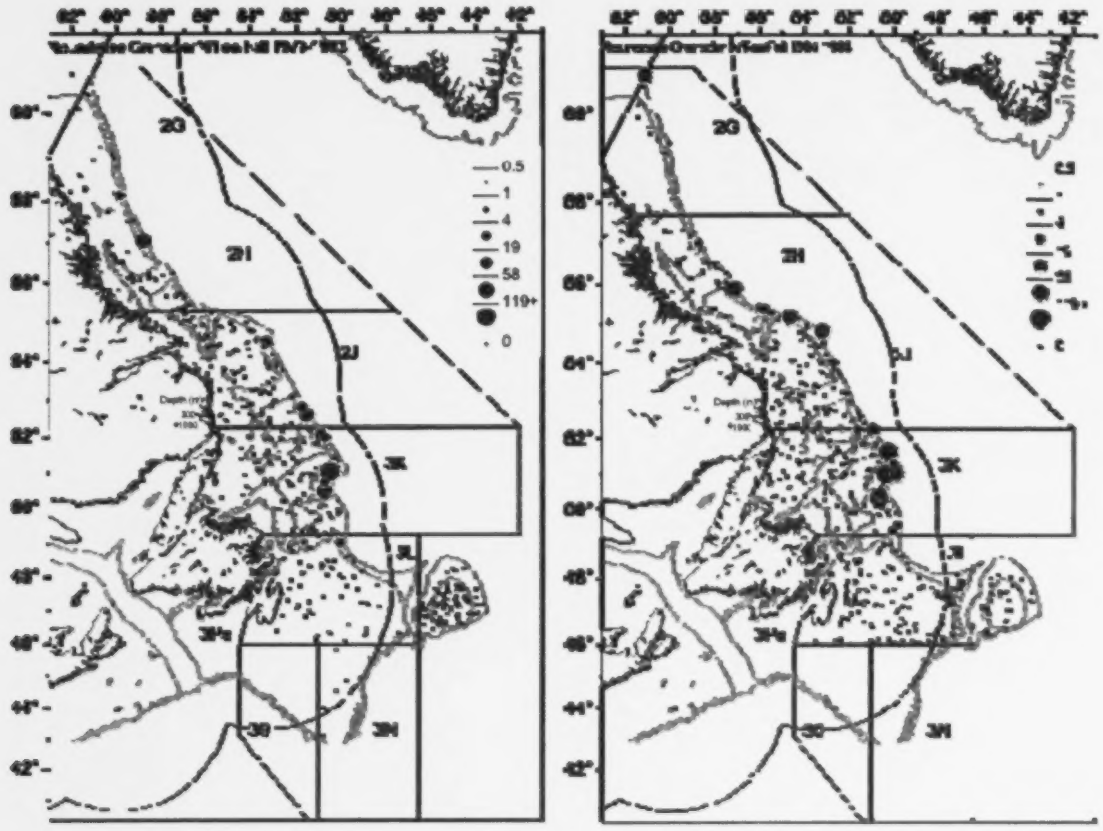

Figure 11. Distribution of Roundnose Grenadier as number per tow; based on Canadian research surveys in autumn 1979-83 and 1984-88 (years combined).

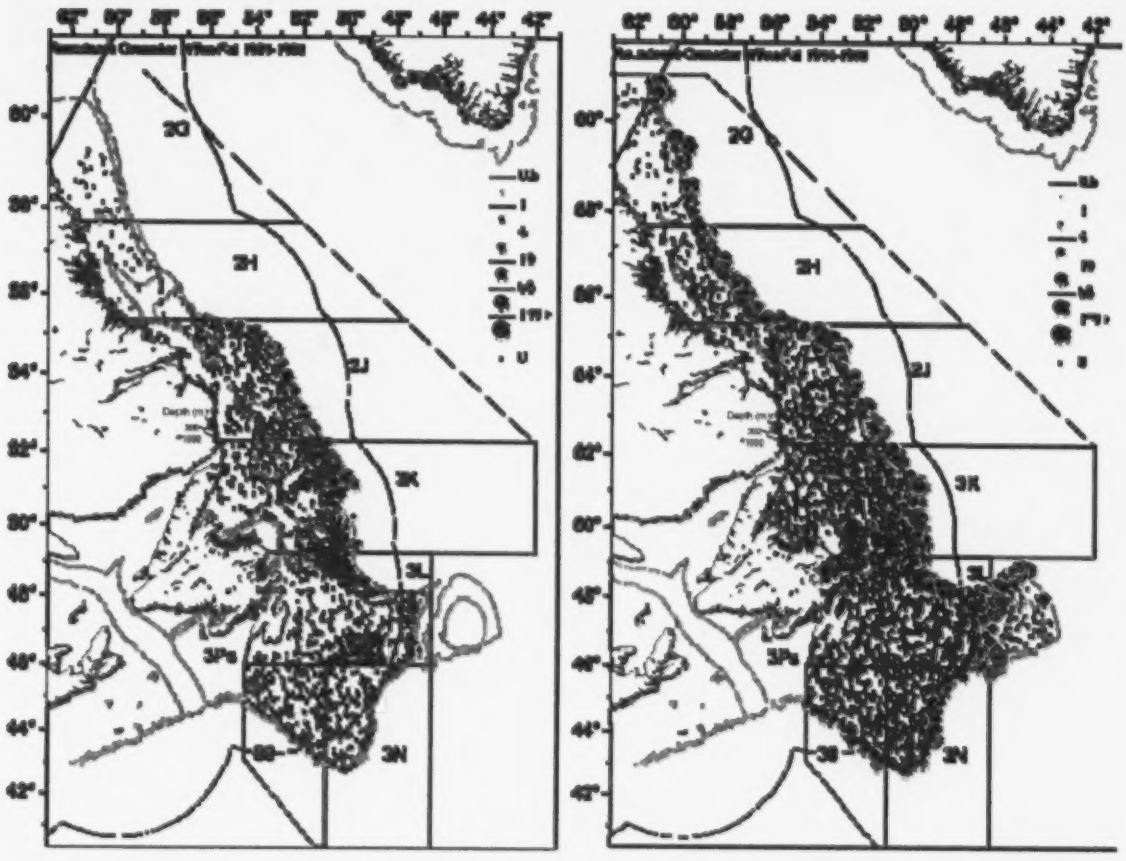

Figure 12. Distribution of Roundnose Grenadier as number per tow; based on Canadian research surveys in autumn 1989-93 and 1994-98 (years combined).

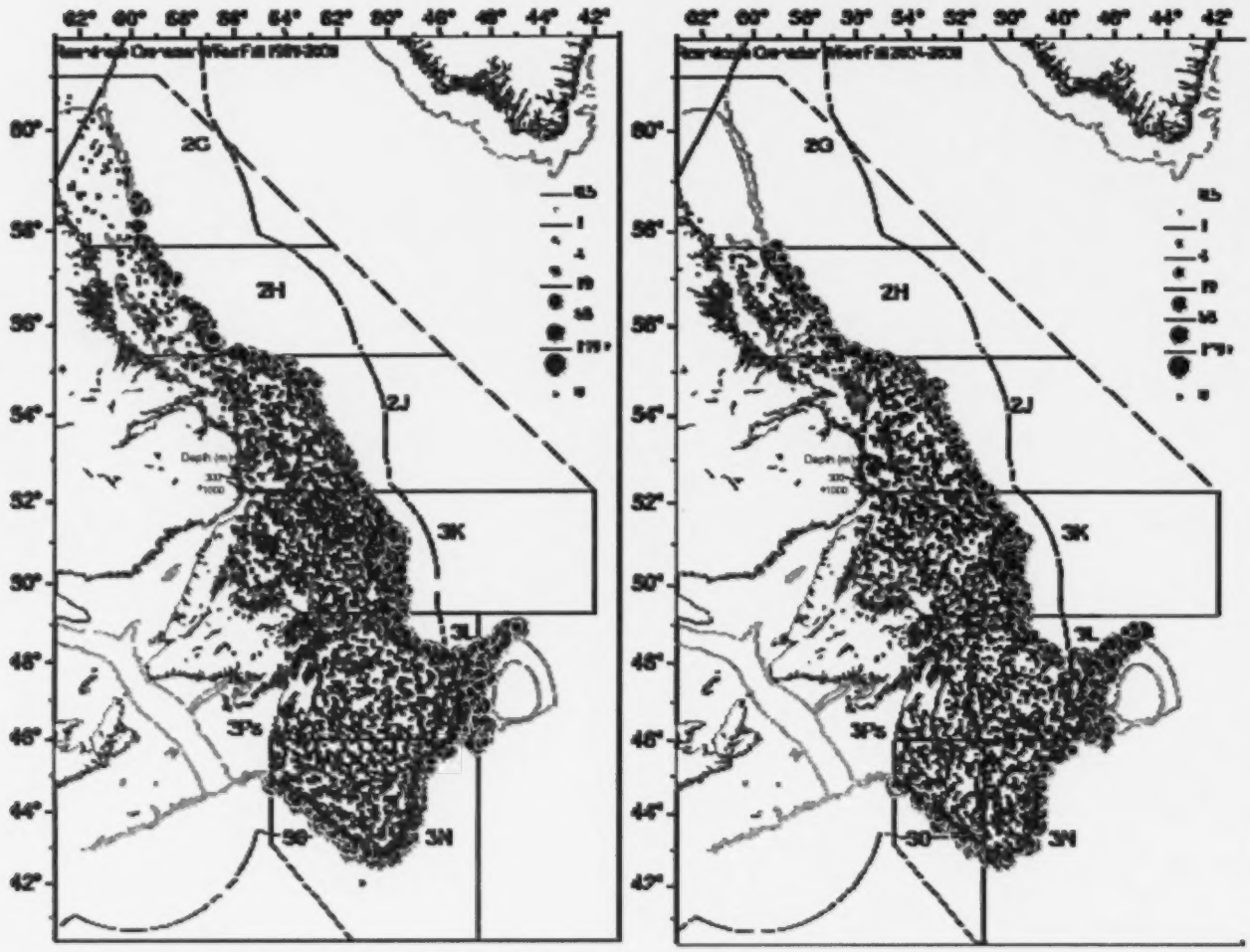

Figure 13. Distribution of Roundnose Grenadier as number per tow; based on Canadian research surveys in autumn 1999-2003 and 2004-08 (years combined).

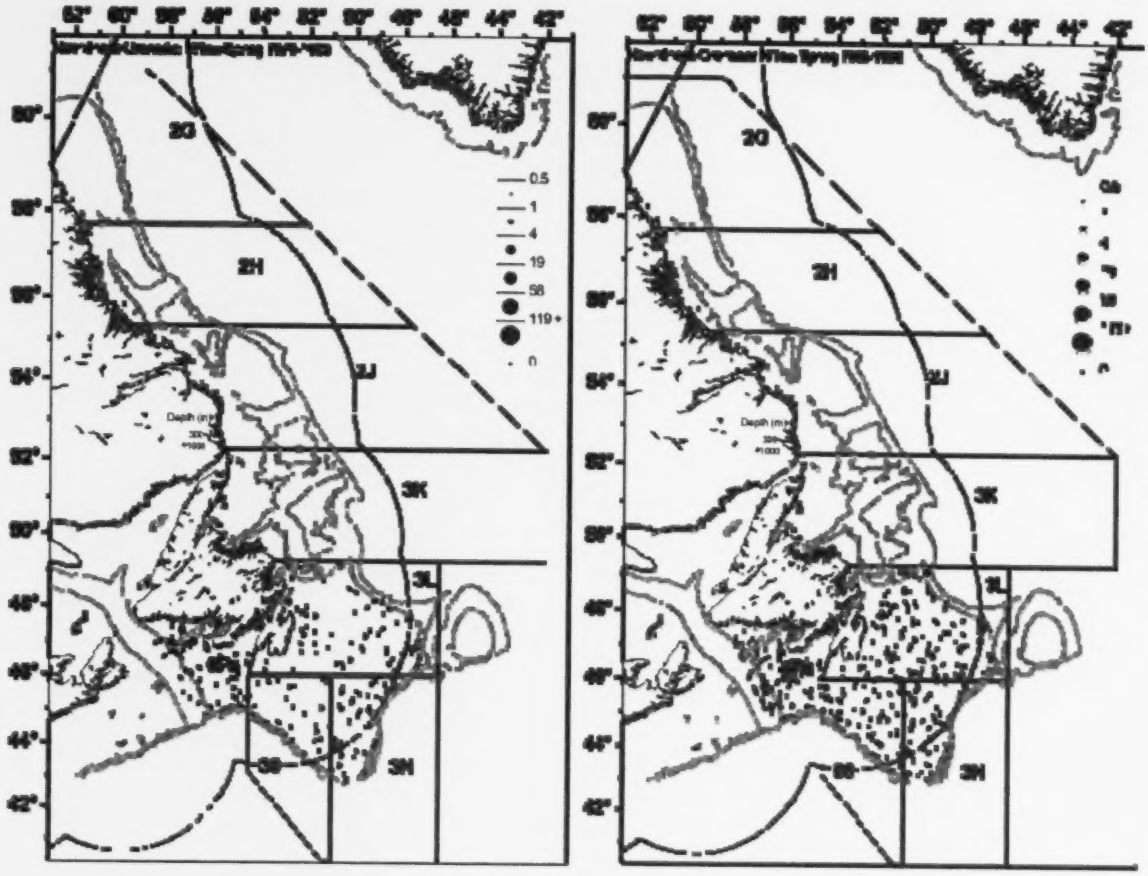

Figure 14. Distribution of Roundnose Grenadier as number per tow; based on Canadian research surveys in spring 1979-83 and 1984-88 (years combined).

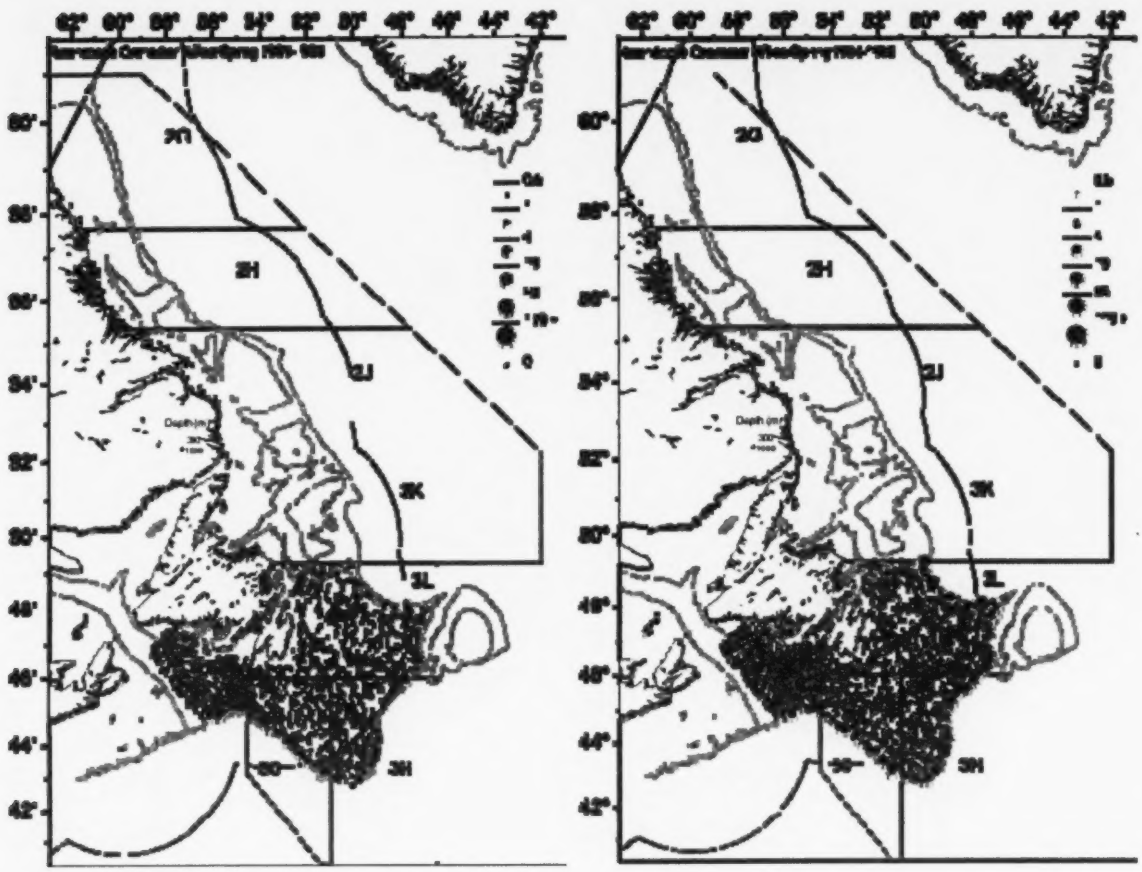

Figure 15. Distribution of Roundnose Grenadier as number per tow; based on Canadian research surveys in spring 1989-93 and 1994-98 (years combined).

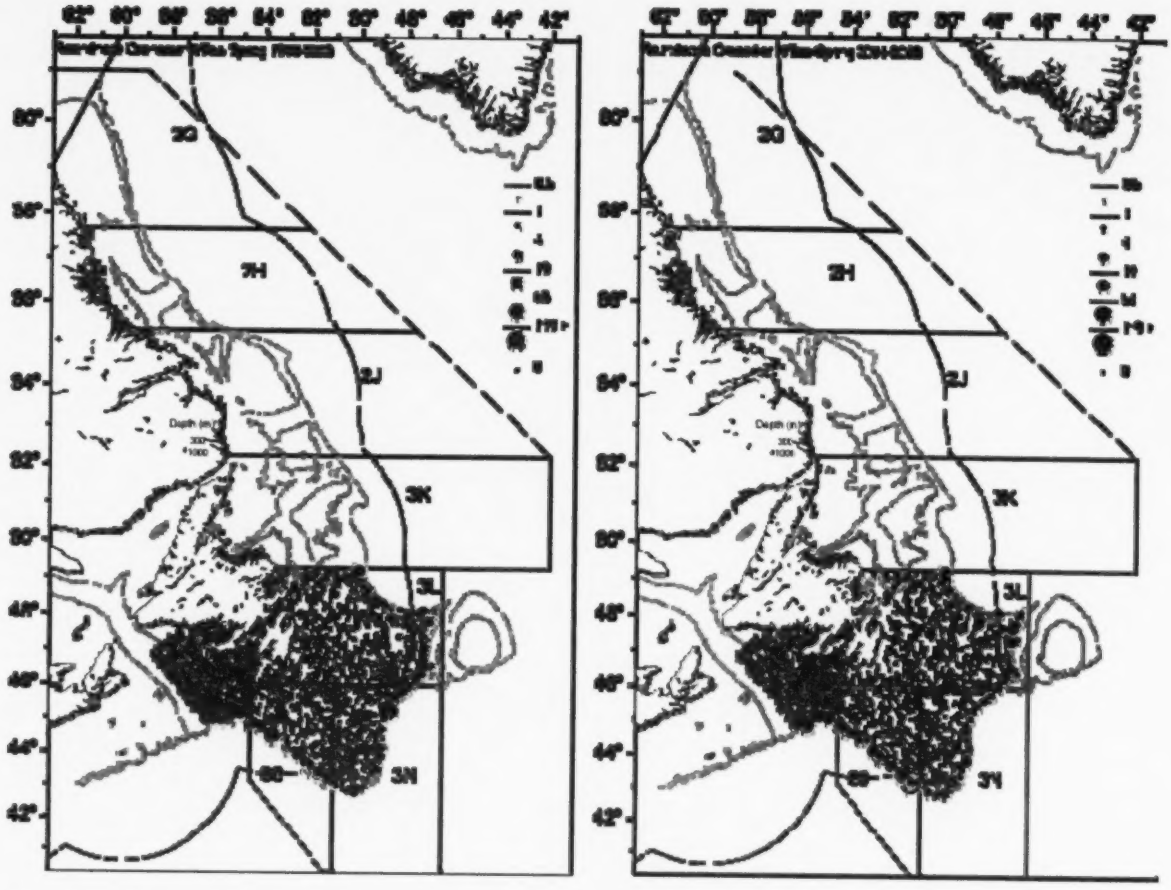

Figure 16. Distribution of Roundnose Grenadier as number per tow; based on Canadian research surveys in spring 1999-2003 and 2004-08 (years combined).

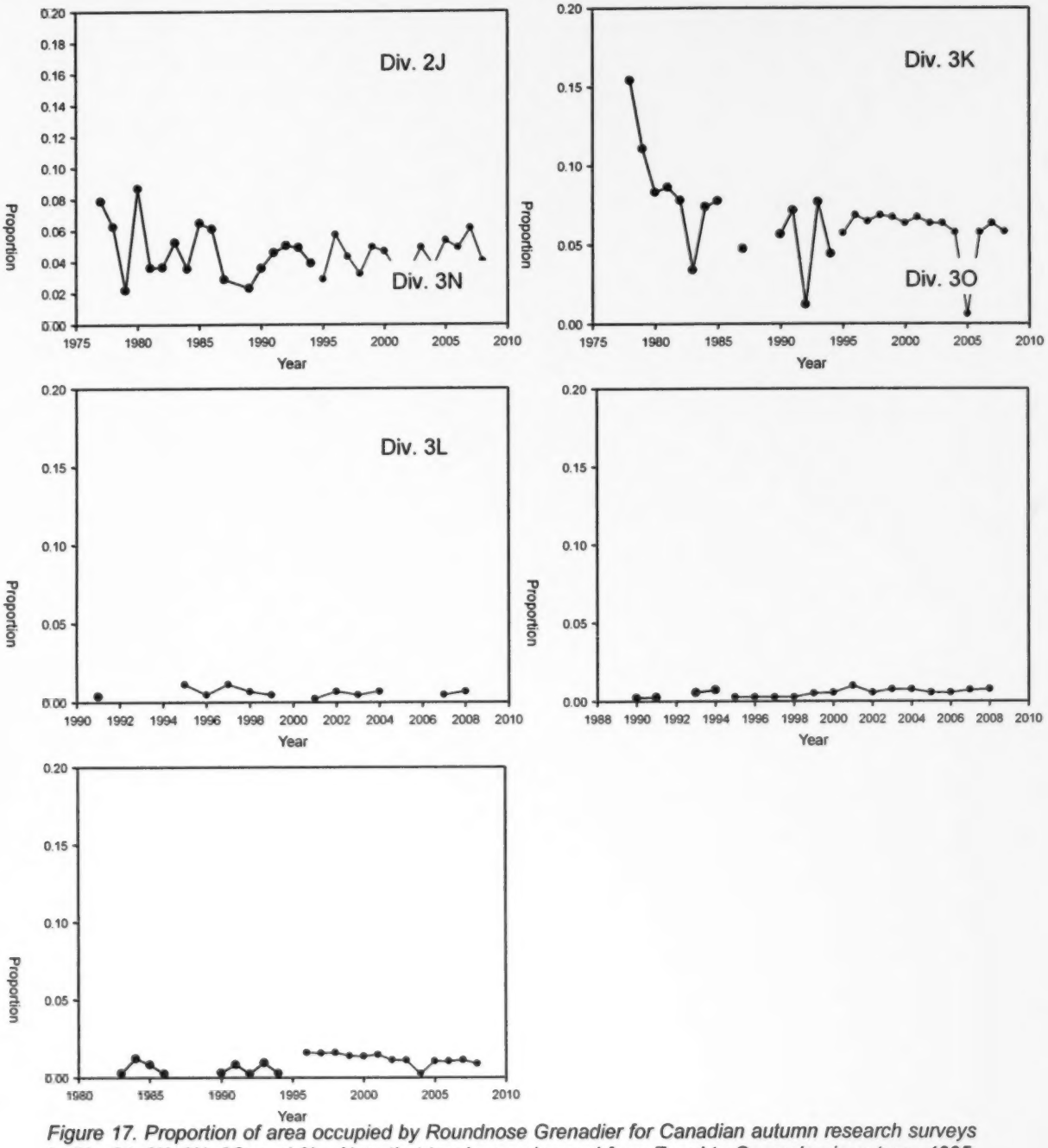

Figure 17. Proportion of area occupied by Roundnose Grenadier for Canadian autumn research surveys in Div. 2J, 3K, 3N, 3O, and 3L. Note that trawl gear changed from Engel to Campelen in autumn 1995. All strata were used for Engel years; while selected strata were used for Campelen years.

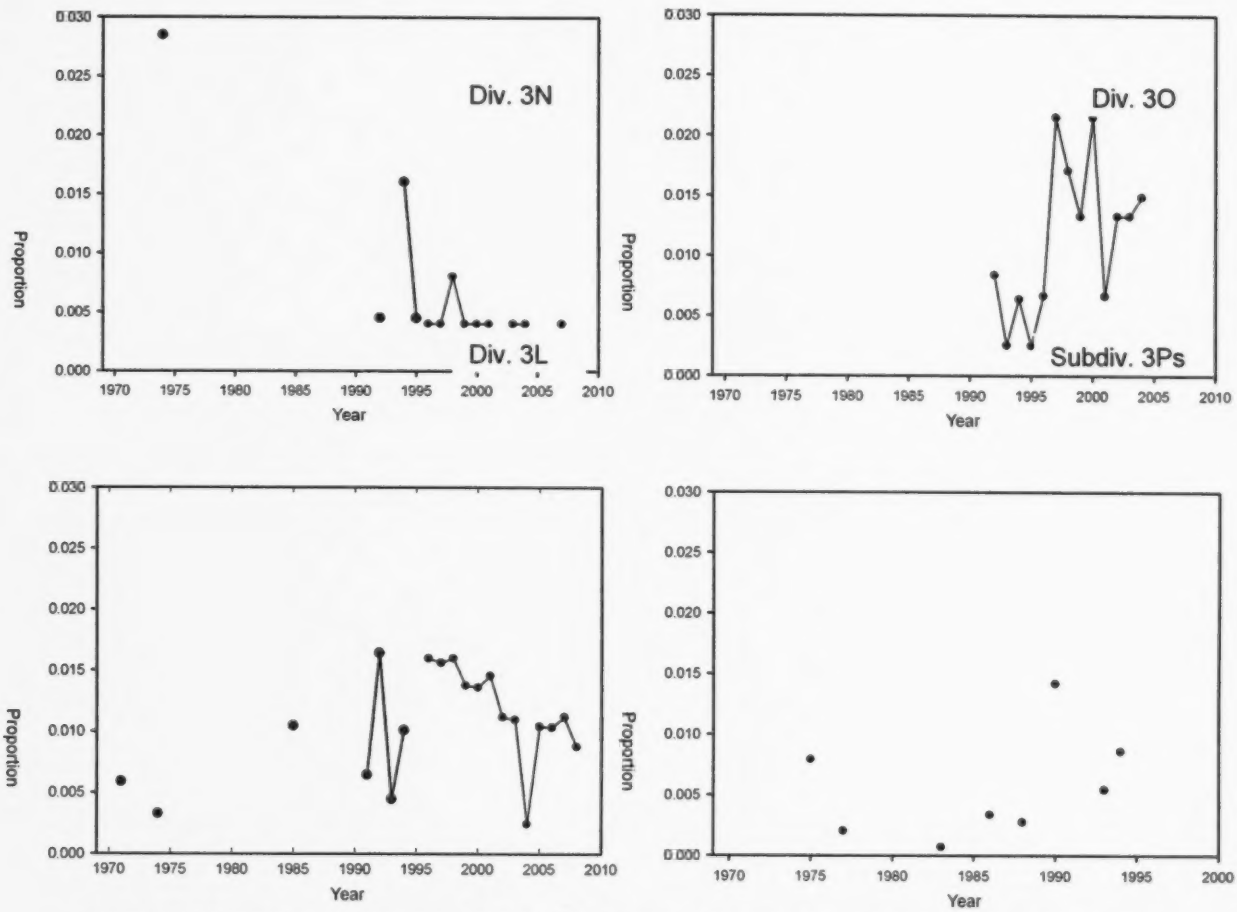

Figure 18. Proportion of area occupied by Roundnose Grenadier for all strata of Canadian spring research surveys in Division 3N, 3O, 3L, and Subdivision 3Ps. Note that trawl gear changed from Yankee to Engel in 1983, and from Engel to Campelen in spring 1996.

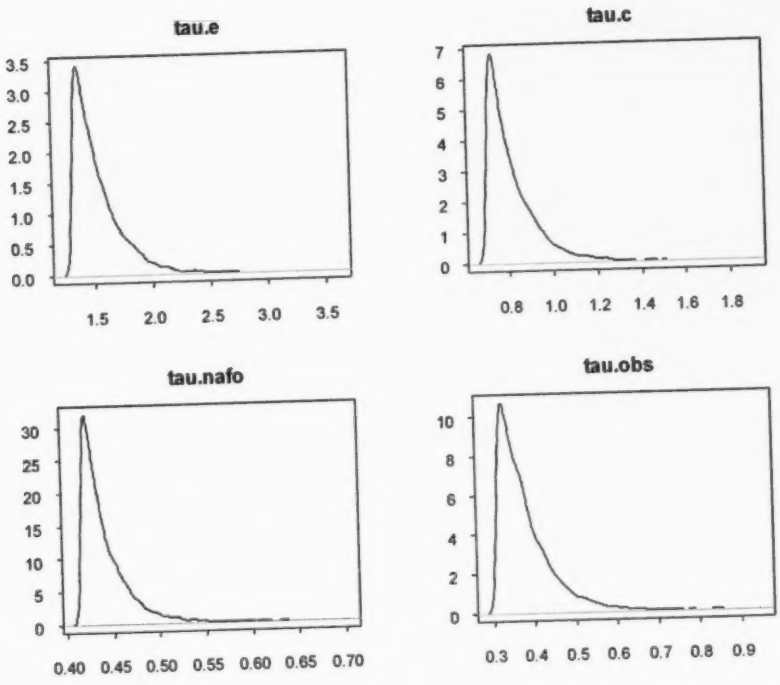

Figure 19a. Posterior densities for selected parameters of the surplus production model for Roundnose Grenadier.

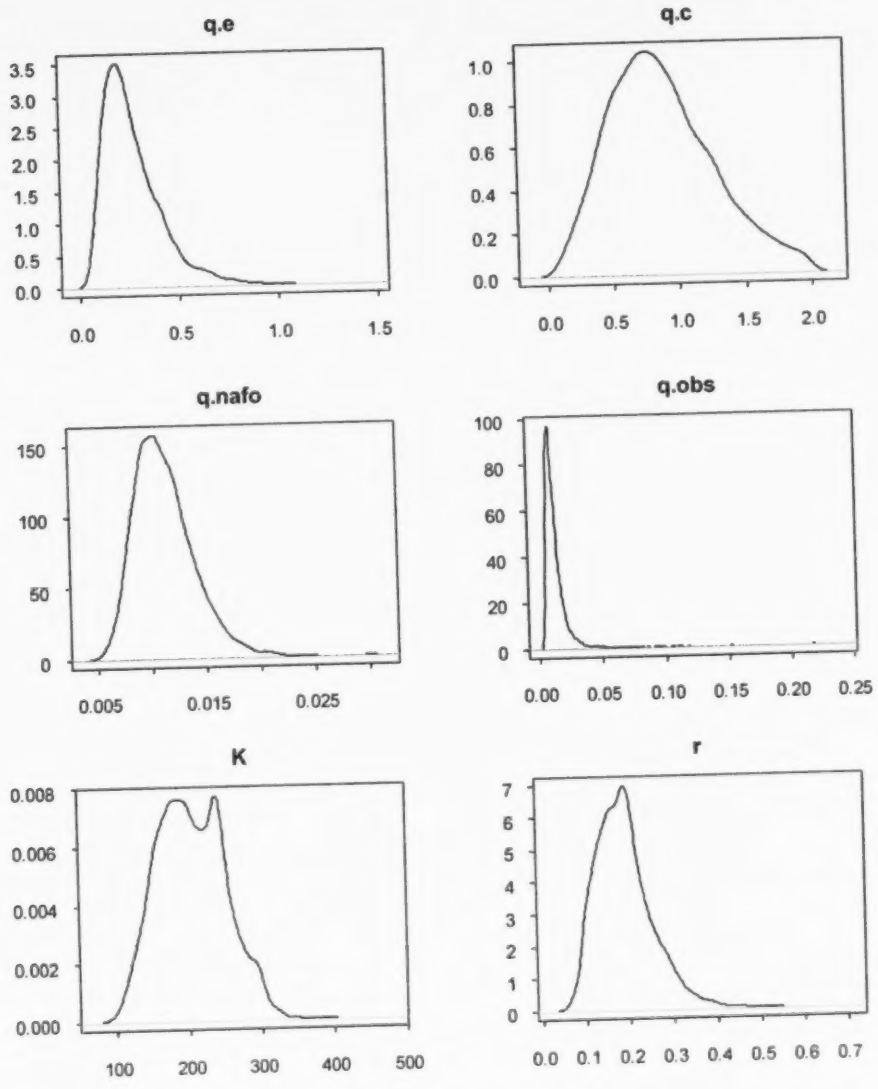

Figure 19b. Posterior densities for selected parameters of the surplus production model for Roundnose Grenadier.

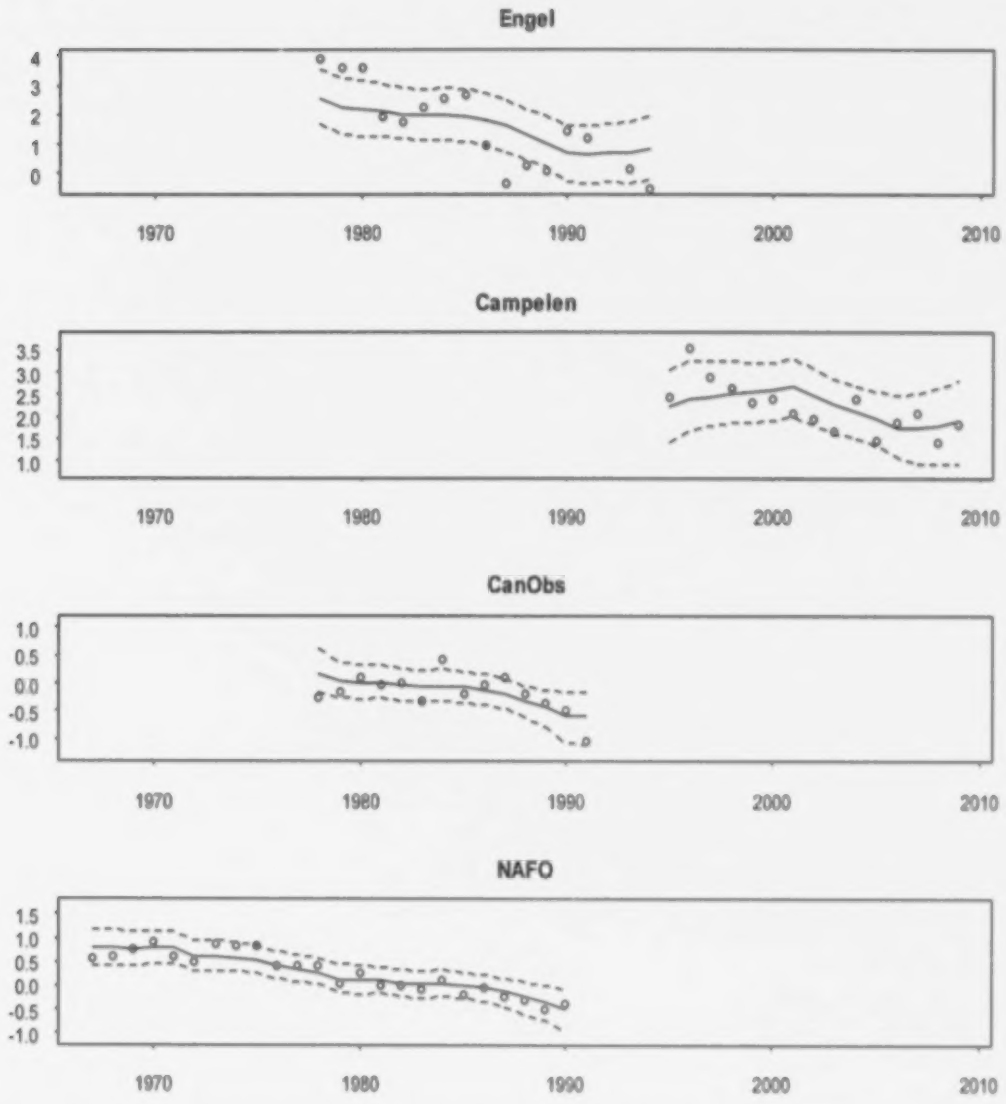

Figure 20. Surplus production model fit to the 4 indices used in the model (○). Median (solid line) and 95 % credible limits (dashed line) of the model fit are indicated.

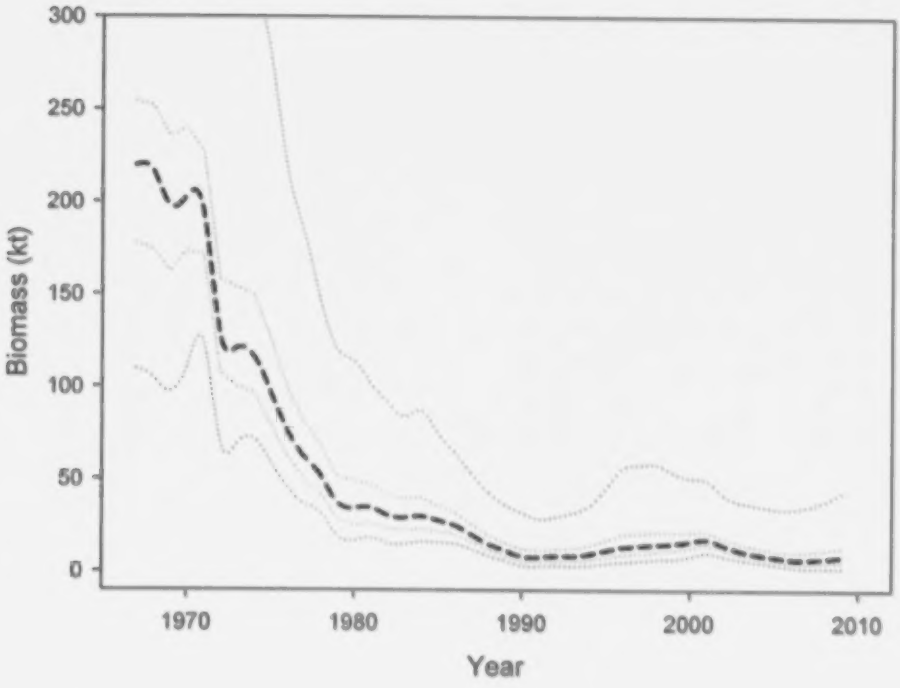

Figure 21. Surplus production model estimates (heavy dashed line) of Roundnose Grenadier biomass in NAFO Subareas 2+3. Dotted lines represent 50 % and 95 % credible intervals.

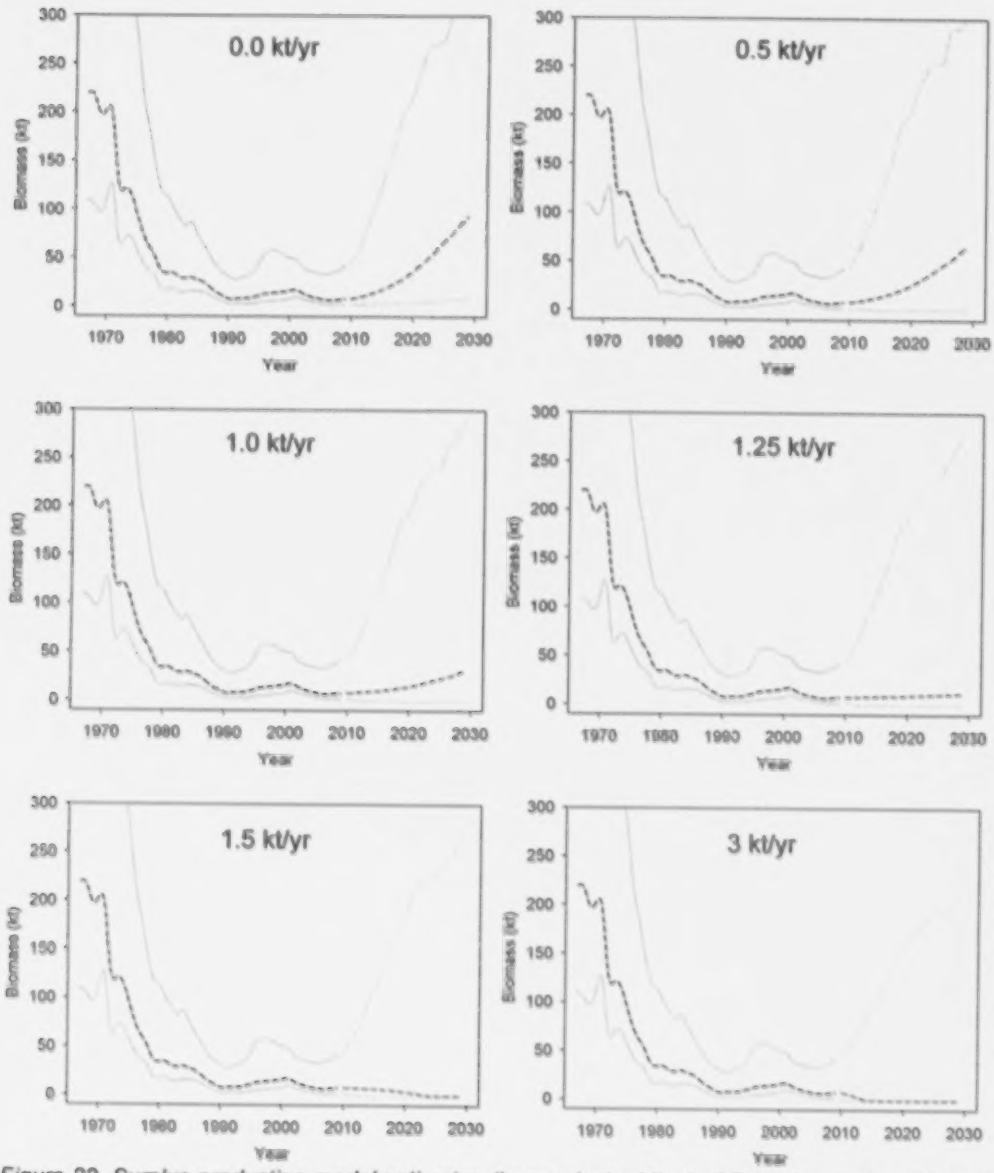

Figure 22. Surplus production model estimates (heavy dashed line) of Roundnose Grenadier biomass in NAFO Subareas 2+3, and projections 20 years forward using various levels of constant catch. Dotted lines represent 95 % credible intervals.

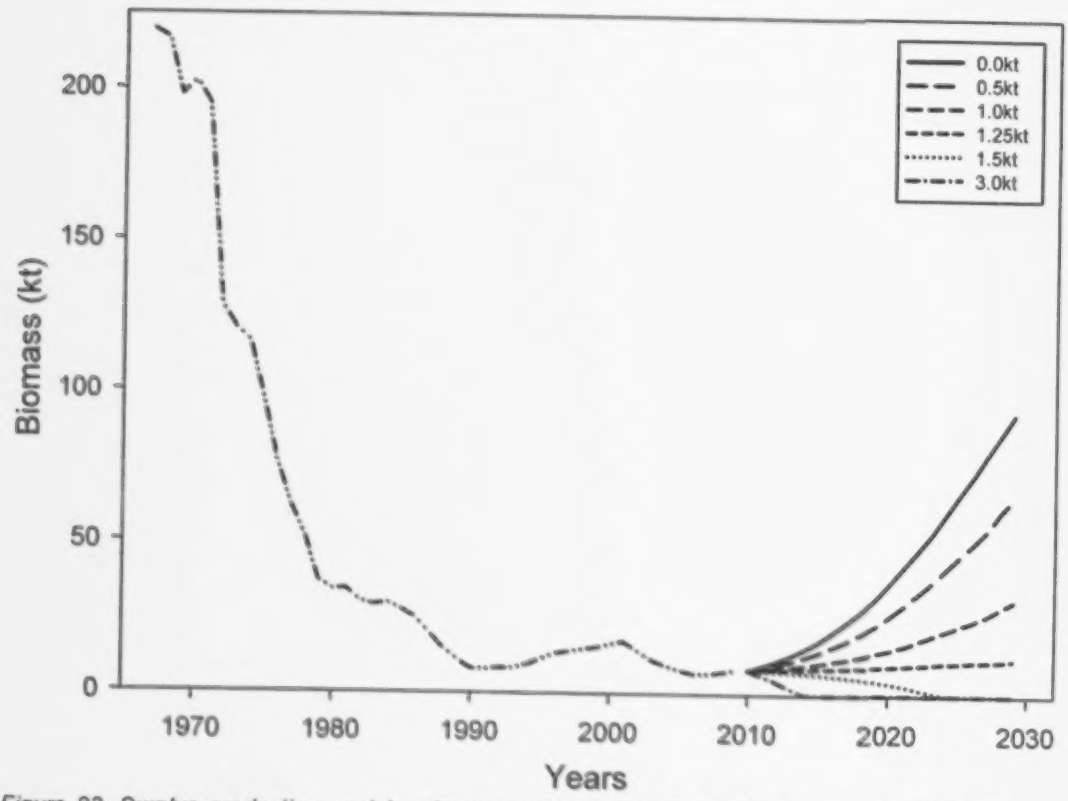

Figure 23. Surplus production model estimates of Roundnose Grenadier biomass in NAFO Subareas 2+3, and projections 20 years forward (2009-29) using various levels of constant catch.

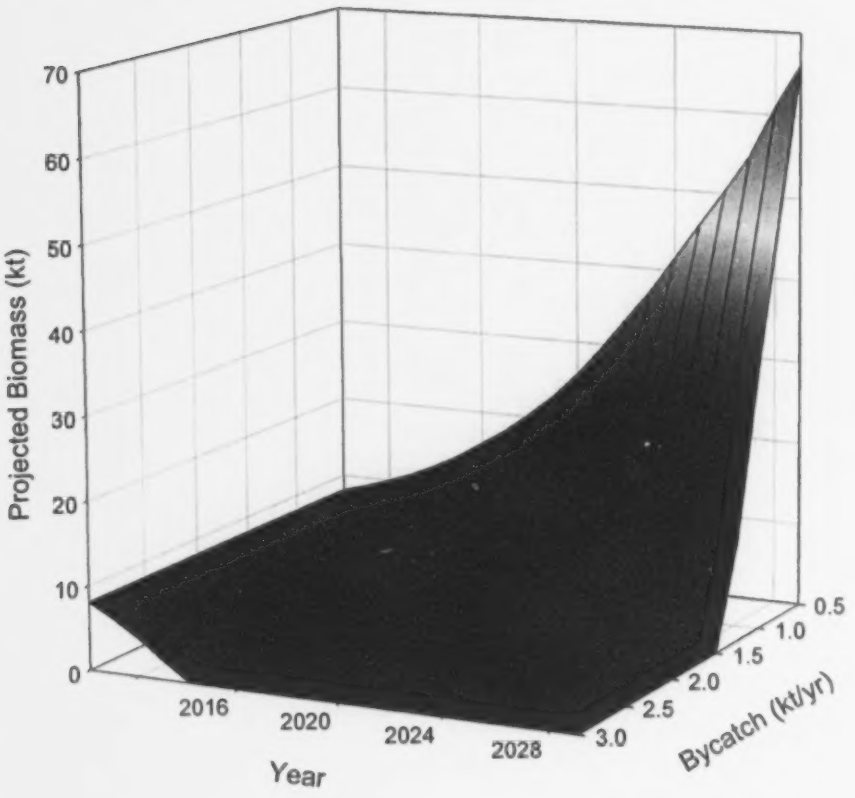

Figure 24. Biomass projections through 20 years as a result of different catch levels.

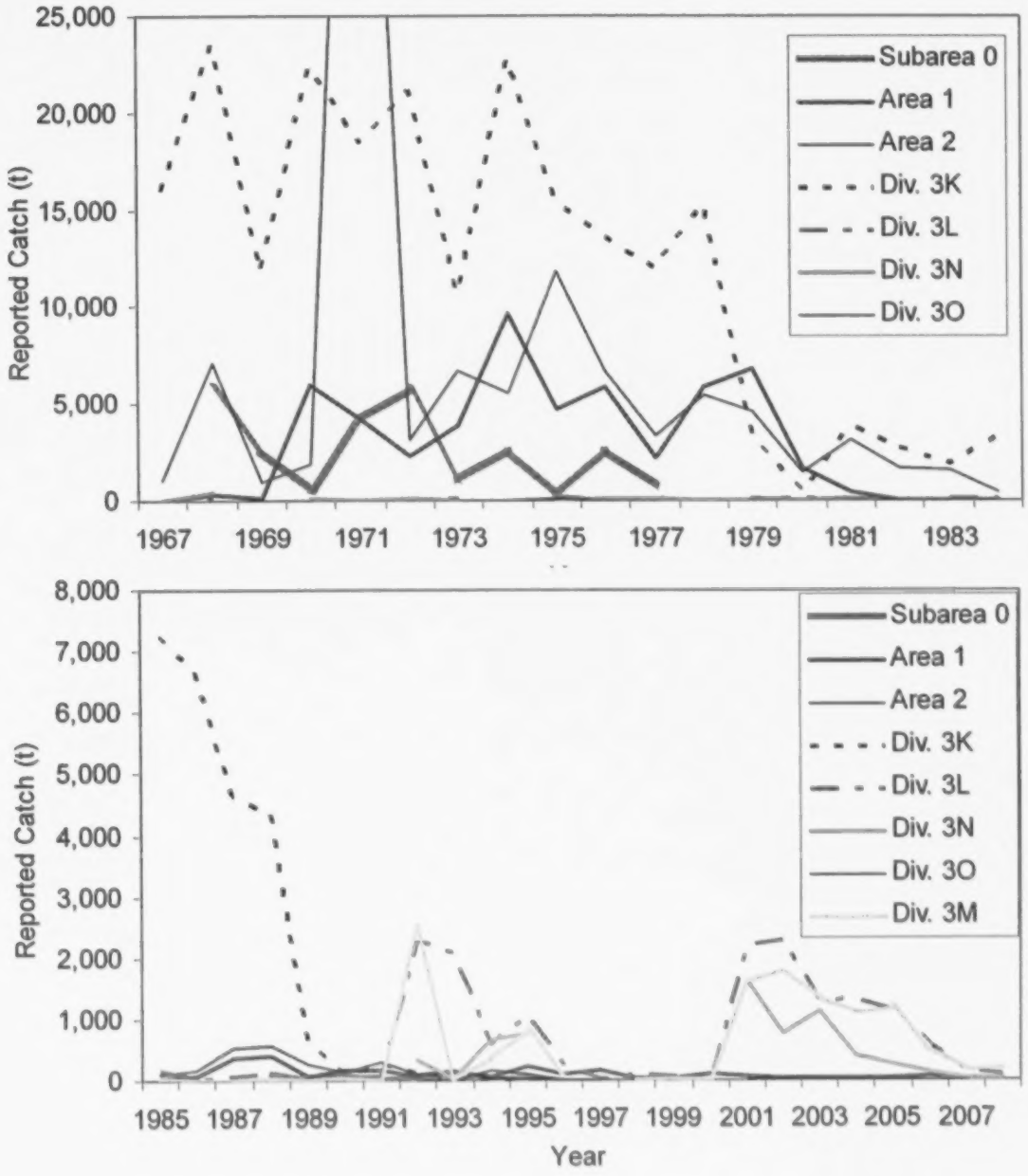

Figure 25. Reported catches of Roundnose Grenadier outside of Canada's 200-mile limit in NAFO Subarea 0, Areas 1 and 2, and Divisions 3KLMNO, 1967-84 (Upper Panel) and 1985-2008 (Lower Panel). Data were collated from NAFO STATLANT-21A, and do not include discards at sea. Note that the Y-axes reflect different scales.

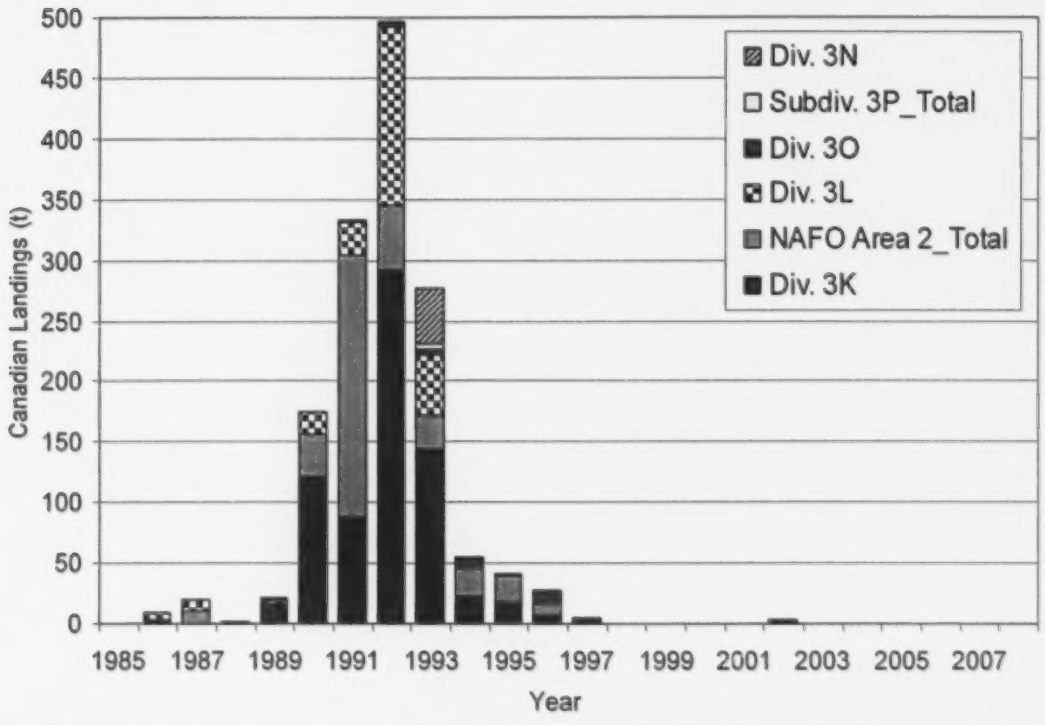

Figure 26. Reported Canadian landings of Roundnose Grenadier inside Canada's 200-mile limit (NAFO Divisions 2GHJ3KLNOP), 1985-2008. Data were tabulated from ZIF, and the 2008 statistics are preliminary.

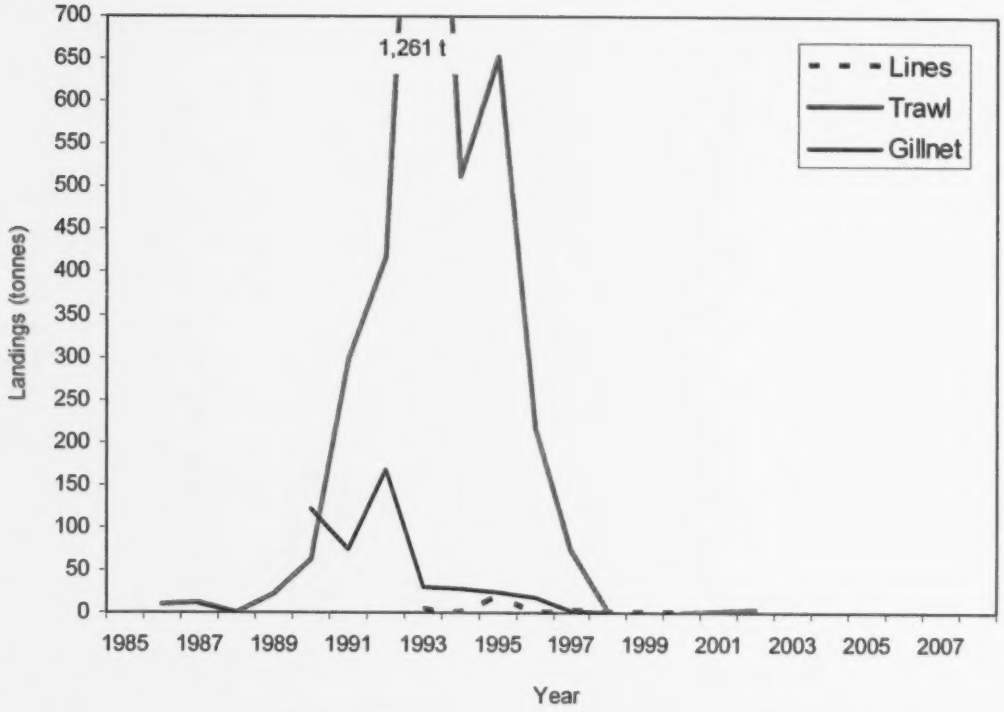

Figure 27. Canadian landings of Roundnose Grenadier by gear type in NAFO Divisions 2GHJ3KLNOP (combined), 1985-2008. Data were tabulated from ZIF, and do not include discards at sea.

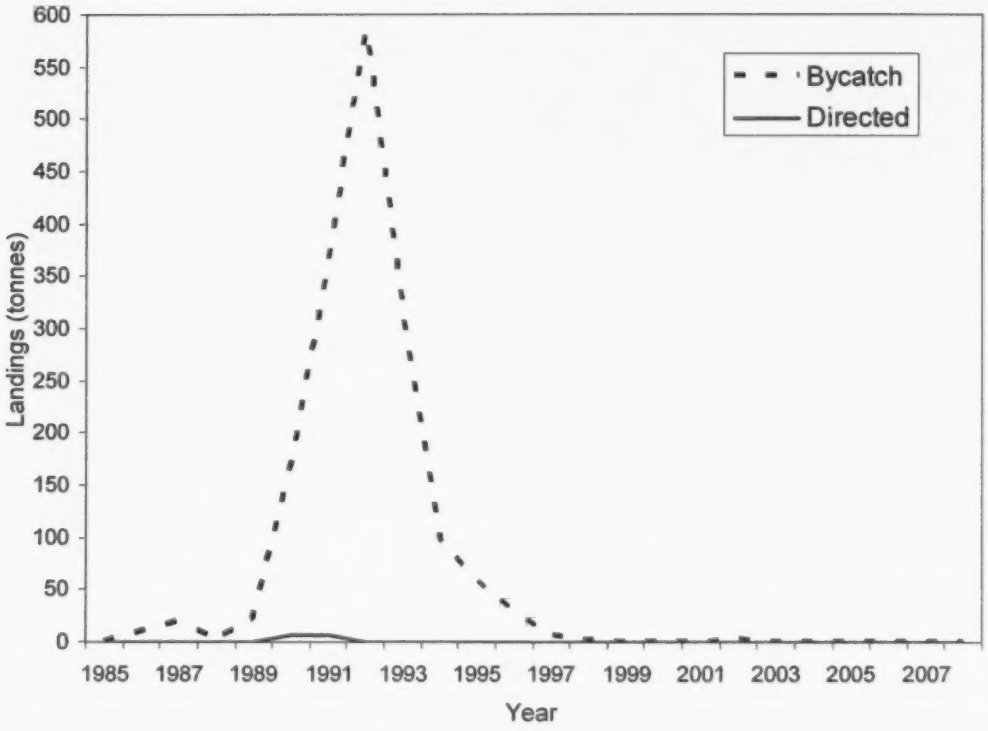

Figure 28. Directed and non-directed Canadian landings of Roundnose Grenadier in NAFO Divisions 2GHJ3KLNOP (combined), 1985-2008. Data were tabulated from ZIF, and do not include discards at sea.

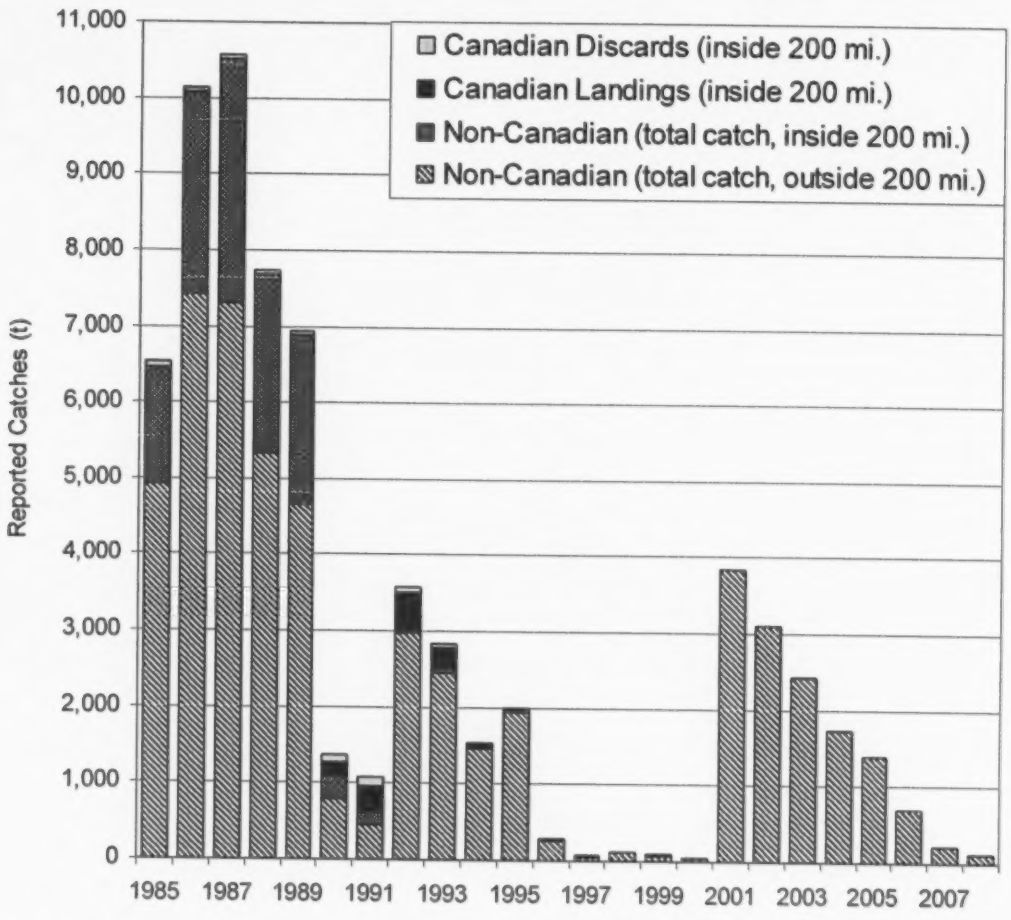

Figure 29. Reported catches of Roundnose Grenadier in NAFO Divisions 2GHJ3KLNOP (combined), 1985-2008. Canadian landings were tabulated from ZIF, discards and non-Canadian catches inside Canada's 200-mile limit were estimated from at-sea Canadian Fisheries Observers data, and non-Canadian catches outside the 200-mile limit were collated from NAFO STATLANT-21A reported data. Data for 2008 are preliminary.

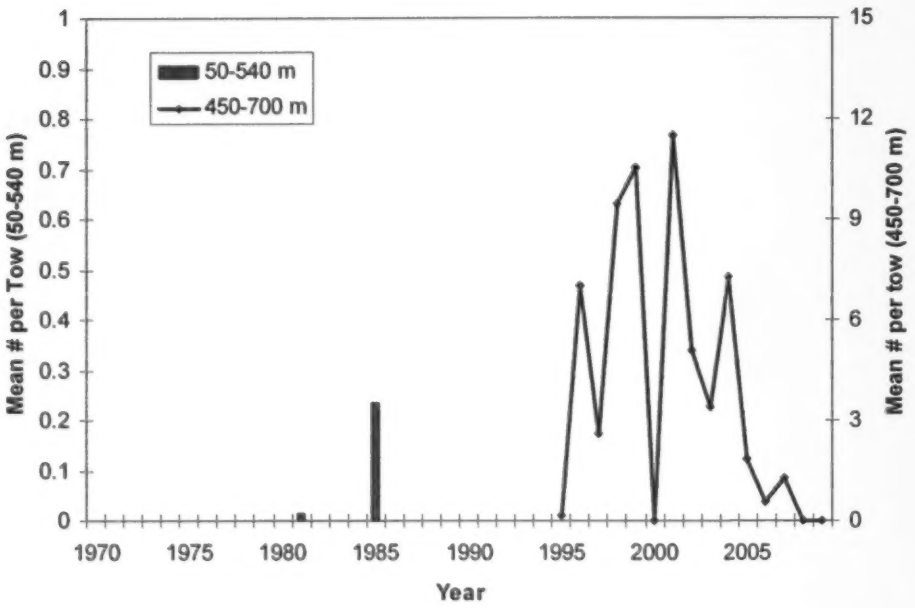

Figure 30. Mean number per tow of Roundnose Grenadier from summer research vessel surveys in NAFO Divisions 4VWX, 1970-2009.

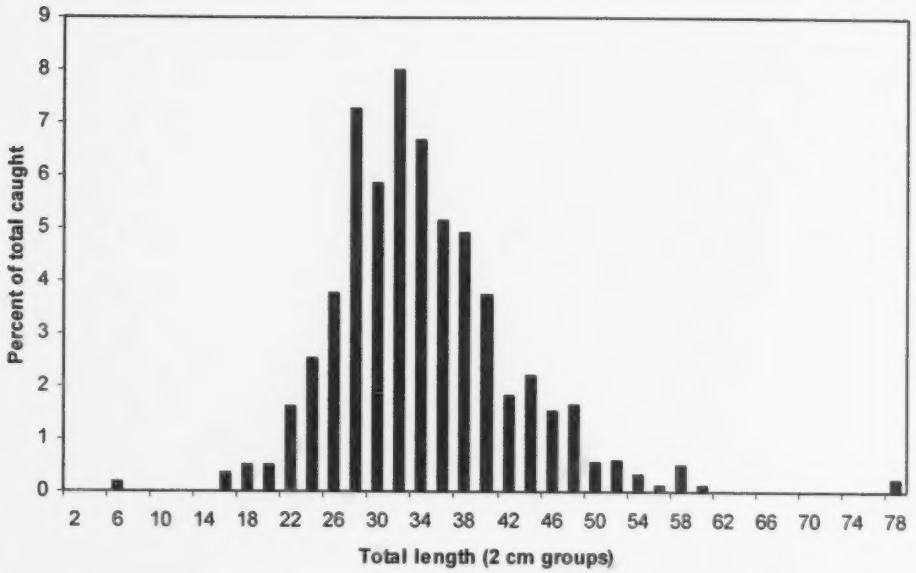

Figure 31. Length frequency distribution of Roundnose Grenadier captured in NAFO Divisions 4VWX by the summer research vessel surveys (1970-2009).

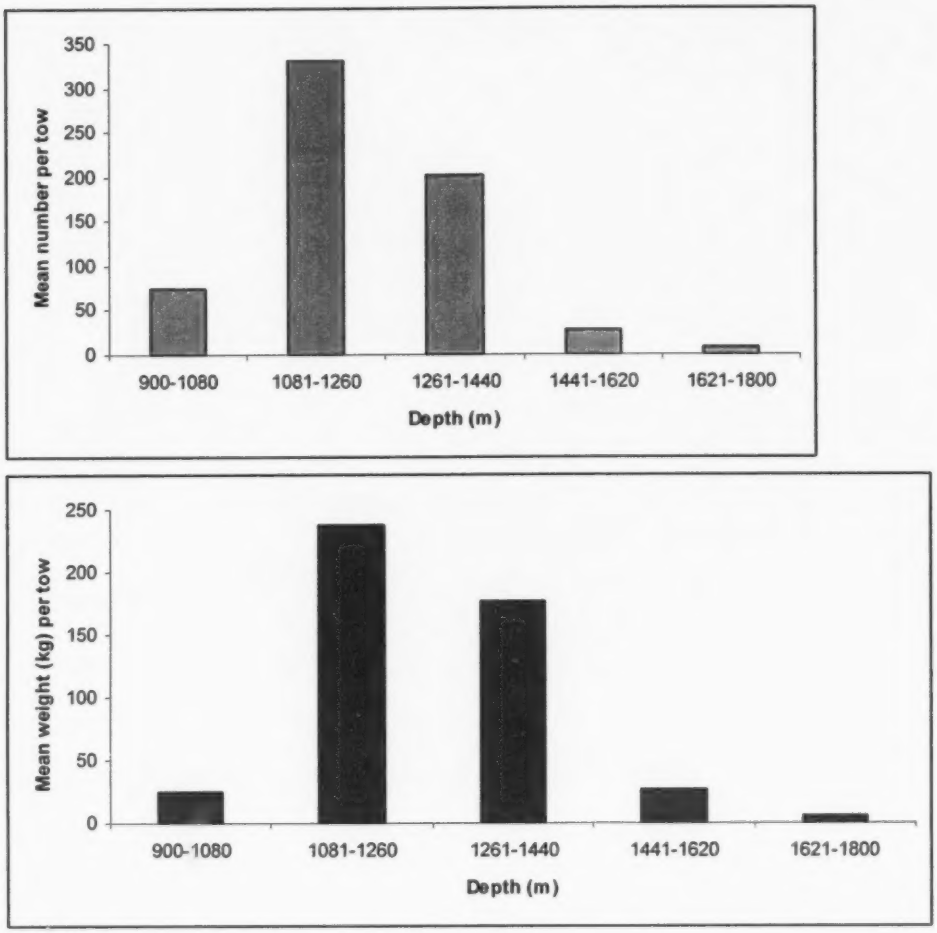

Figure 32. Mean number (above) and mean weight (below) per standardized tow by depth strata of Roundnose Grenadier captured in 4VWX by the Cape Chidley surveys (1994 and1995).

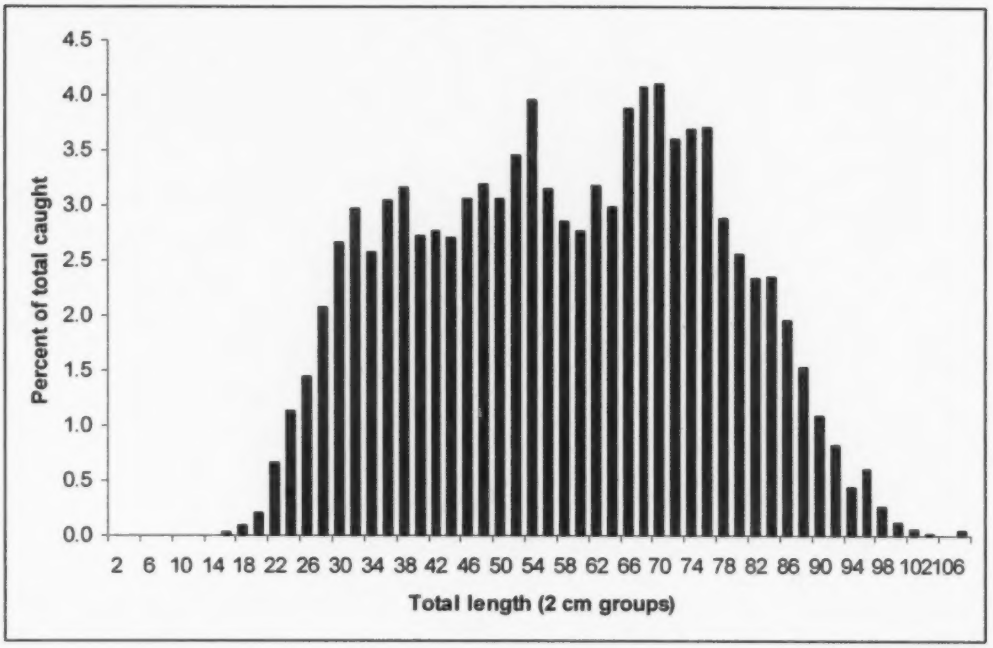

Figure 33. Length frequency distribution of Roundnose Grenadier captured in NAFO Divisions 4VWX by the Cape Chidley surveys in 1994 and 1995.

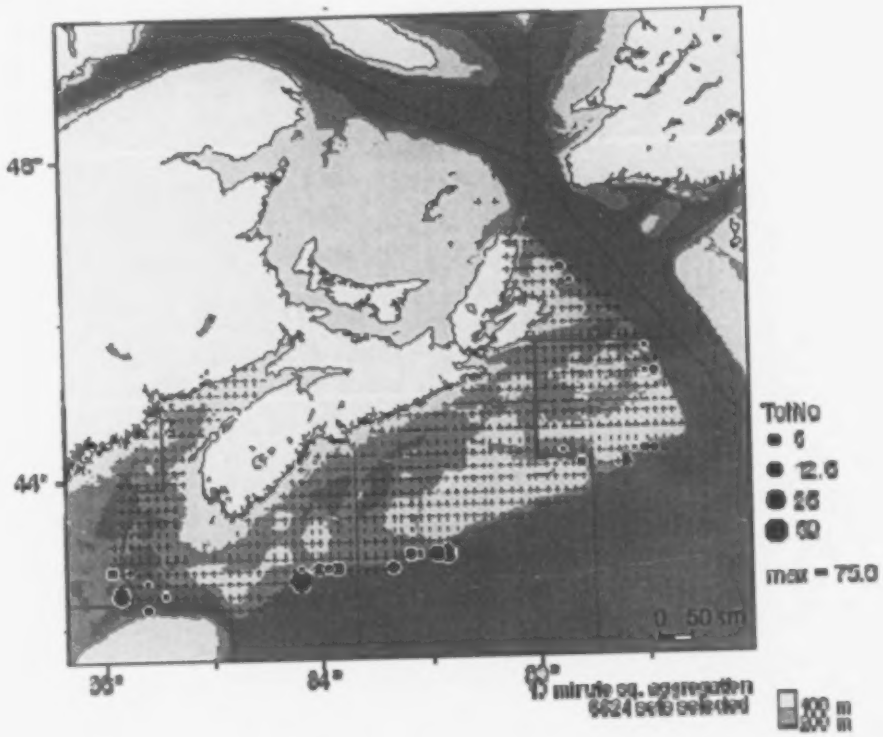

Figure 34. Distribution of Roundnose Grenadier as numbers per tow in summer research vessel surveys of NAFO Divisions 4VWX (1970-2009) sampling 50-720 m depths. Expanding symbols indicate number per tow.

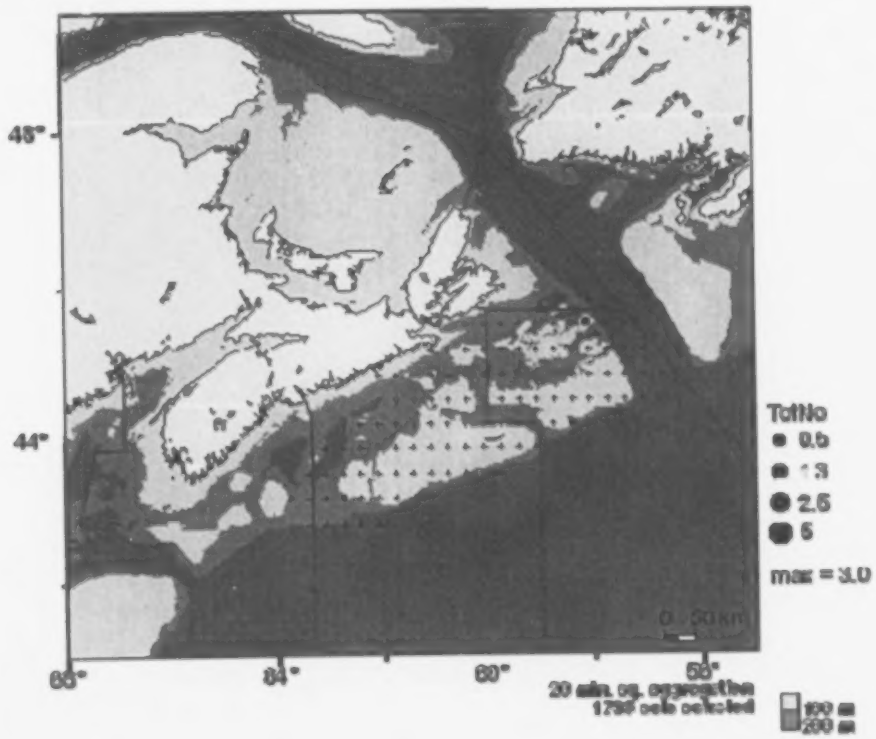

Figure 35. Distribution of Roundnose Grenadier as numbers per tow in spring research vessel surveys of NAFO Divisions 4VW (1986-2007) sampling 50-540 m depths. Expanding symbols indicate number per tow.

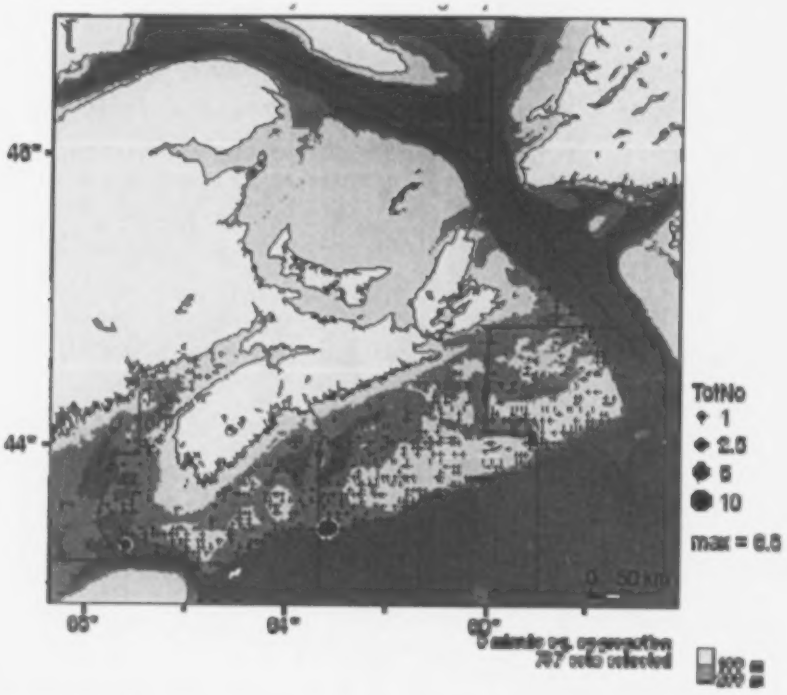

Figure 36. Distribution of Roundnose Grenadier as numbers per tow in spring research vessel surveys of NAFO Divisions 4VWX (1978-84) sampling 50-540 m depths. Expanding symbols indicate number per tow.

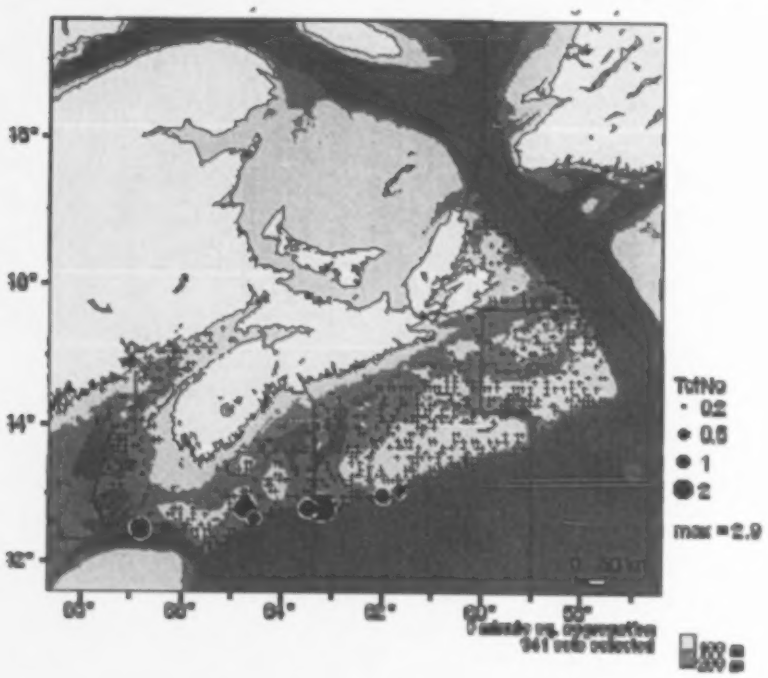

Figure 37. Distribution of Roundnose Grenadier as numbers per tow in autumn research vessel surveys of NAFO Divisions 4VWX (1978-84) sampling 50-540 m depths. Expanding symbols indicate number per tow.

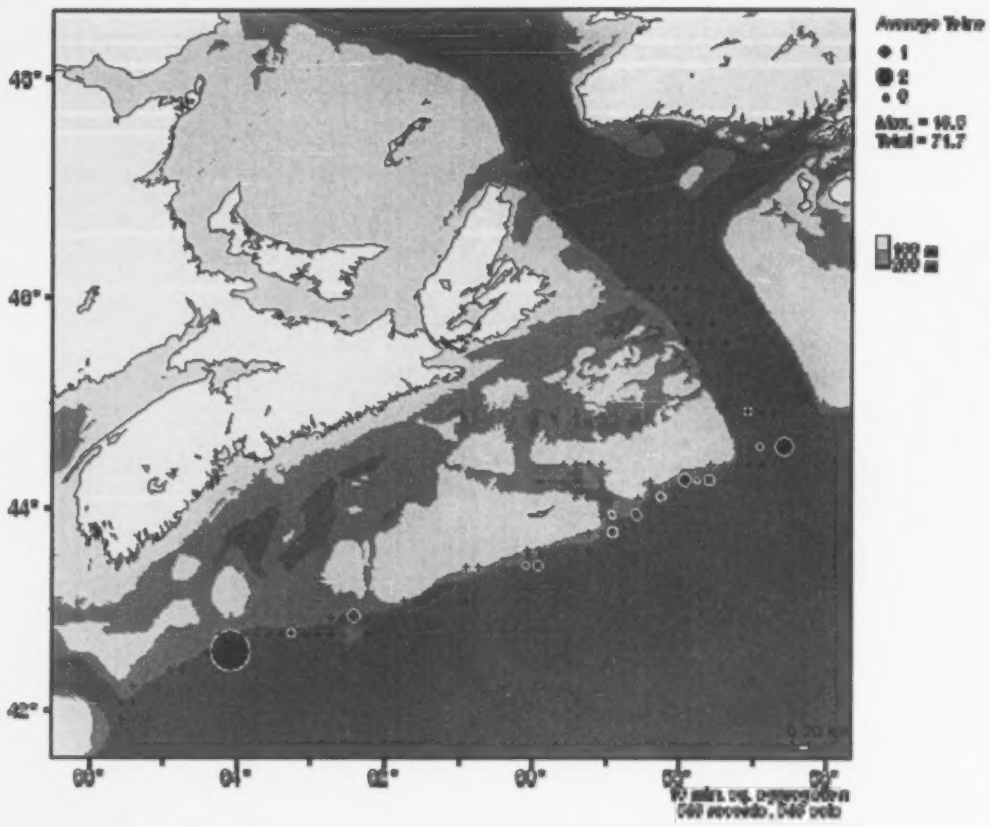

Figure 38. Distribution of Roundnose Grenadier as numbers per tow in redfish research vessel surveys of NAFO Divisions 4VWX (1982-88) sampling 200-900 m depths. Expanding symbols indicate number per tow.

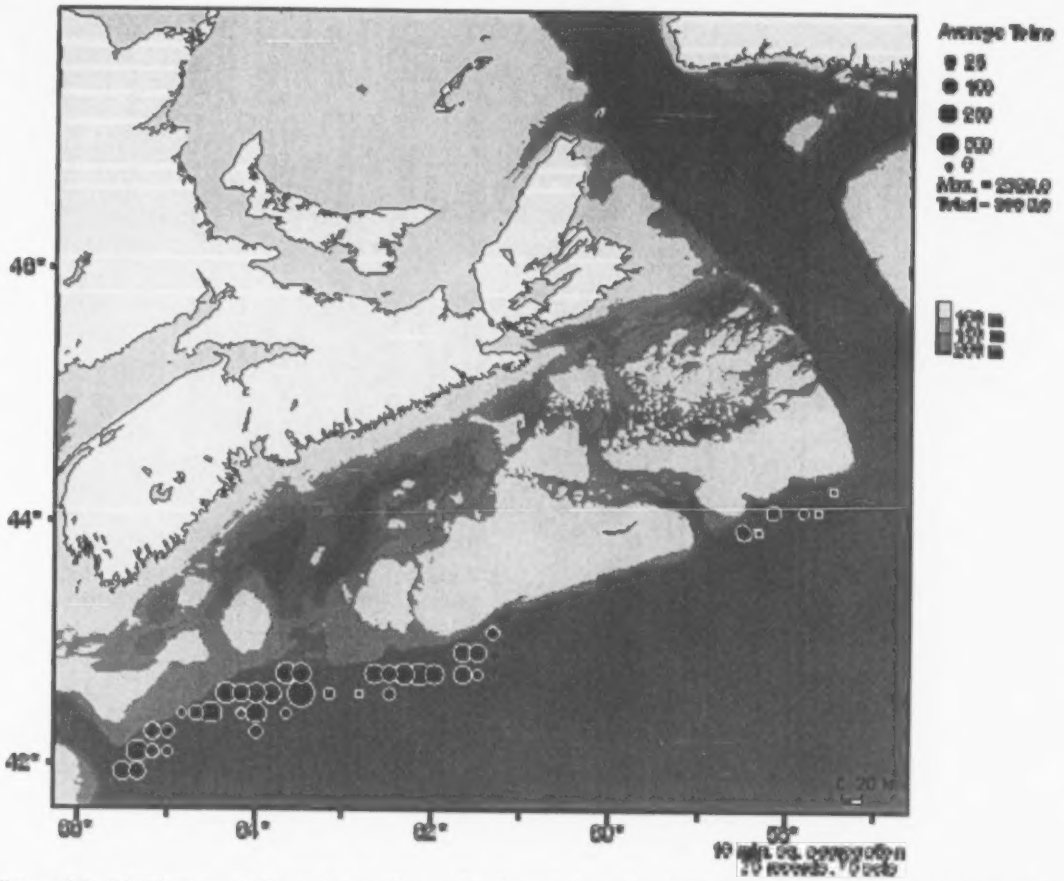

Figure 39. Distribution of Roundnose Grenadier in collaborative DFO-Industry surveys of 4VWX by the Cape Chidley in 1994-95, sampling depths of 900-1800 m. Expanding symbols indicate number per tow.

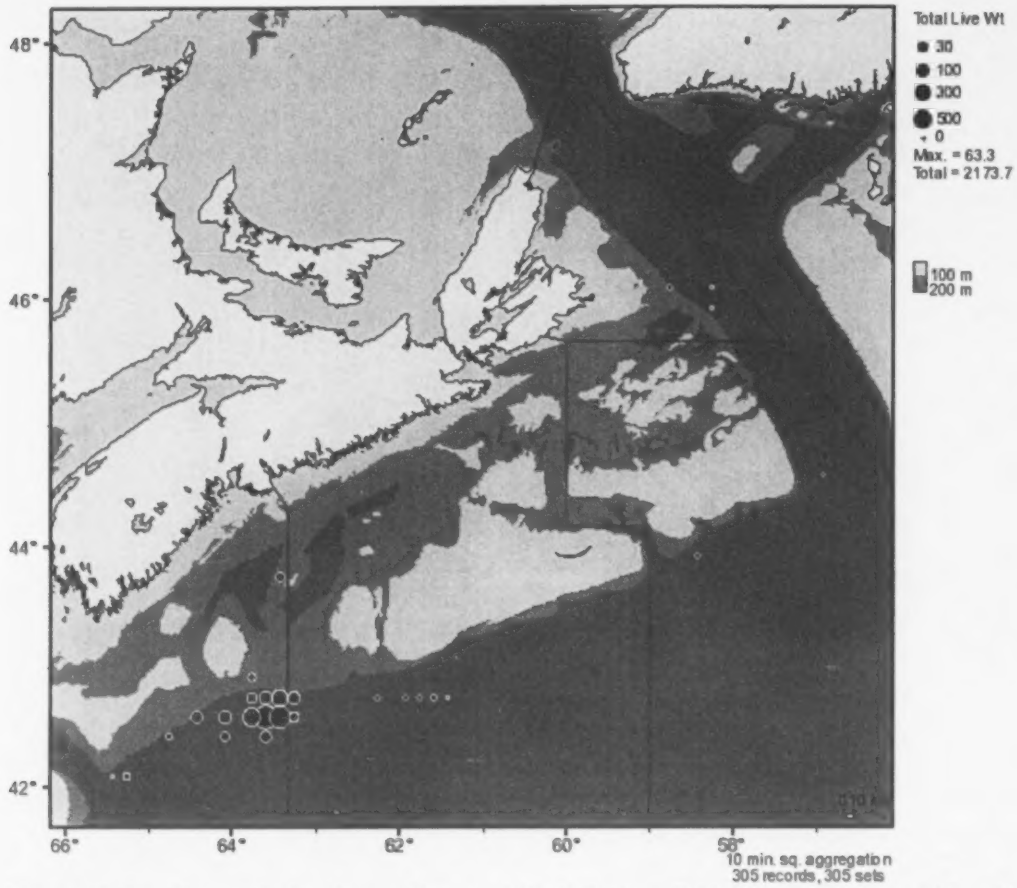

Figure 40. Location and size (expanding symbols indicate weight in kg) of commercial catches of Roundnose Grenadier in NAFO Division 4VWX from 1993 to 1997, based on Maritime Observer data.

Appendix 1. Sample WinBUGS script for Roundnose Grenadier surplus production model.

```
{
# Prior for intrinsic rate of increase, r
r ~ dlnorm(-1.09,4.03)I(0.001,1.5)

# prior distribution of q's
q.e~dunif(0,2)
q.c~dunif(0,2)
q.obs~dunif(0,2)
q.nafo~dunif(0,2)

# prior distribution of K
K~dlnorm(5.01,10.6)

#exponent distributions
x~dunif(0,2)
y~dunif(0,2)

# Prior for process noise, sigma
sigma ~ dunif(0,10)
isigma2 <- pow(sigma, -2)

# Prior for observation errors
tau.e~dunif(1.31,3.92)
itau2.e <- pow(tau.e, -2)
tau.c~dunif(0.70,2.11)
itau2.c <- pow(tau.c, -2)
tau.obs~dunif(0.309,0.93)
itau2.obs <- pow(tau.obs, -2)
tau.nafo~dunif(0.416,1.25)
itau2.nafo <- pow(tau.nafo, -2)

# Prior for initial population size as proportion of K, P[1].
Pm[1] <- log(1)
P[1] ~ dlnorm(Pm[1], isigma2)I(0.0001,5)

# State equation - SP Model.
for (t in 2:(43))  {
Pm[t] <- log(max(P[t-1] + r*P[t-1]*(1-P[t-1]) - C[t-1]/K, 0.0001))
P[t] ~ dlnorm(Pm[t], isigma2)I(0.0001,5)
}

# Observation equation.
for (t in 12:(28)) {
lengm[t] <- log(q.e*K * P[t])
leng[t] ~ dlnorm(lengm[t], itau2.e)
}

for (t in 29:(43)) {
lcamm[t] <- log(q.c*K * P[t])
lcam[t] ~ dlnorm(lcamm[t], itau2.c)
}
```

```
for (t in 12:(25)) {
lobsm[t] <- log(q.obs*K * (pow(P[t],x)))
lobs[t] ~ dlnorm(lobsm[t], itau2.obs)
}

for (t in 1:(24)) {
lnafom[t] <- log(q.nafo*K * (pow(P[t],y)))
lnafo[t] ~ dlnorm(lnafom[t], itau2.nafo)
}

# Output. Using the proportion and K to estimate biomass, B.
for(t in 1:N) {
B[t] <- P[t] * K
}
} ## EN
```